UNITED STATES PATENT AND TRADEMARK OFFICE
BEFORE THE PATENT TRIAL AND APPEAL BOARD

APPLE INC.,)
)
Petitioner,)
) Case Nos.
vs.) IPR2022-01299
)
MASIMO CORPORATION,)
) U.S. Patent
Patent Owner.) 7,761,127
)

DEPOSITION OF DR. WILLIAM P. KING
August 8, 2023
10:00 a.m.

Reported by: Eileen Mulvenna, CSR/RMR/CRR

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REMOTE VIDEOTAPED DEPOSITION of

DR. WILLIAM P. KING, Declarant for Patent Owner in the above-titled action, held on Tuesday, August 8, 2023, commencing at approximately 10:00 a.m., before Eileen Mulvenna, CSR/RMR/CRR, Certified Shorthand Reporter, Registered Merit Reporter, Certified Realtime Reporter, and Notary Public of the State of New York.

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I N D E X

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THE REPORTER: Before swearing in the witness, I have a short statement for the record.

The attorneys participating in this deposition acknowledge that I am not physically present in the deposition room and that I will be reporting this deposition remotely. They further acknowledge that, in lieu of an oath administered in person, I will administer the oath.

Do all counsel consent to this arrangement and waive any objections to this manner of reporting?

MR. STEPHENS: That's fine with Petitioner. We consent.

MR. CANNON: That's fine with Patent Owner.

DR. WILLIAM P. KING,

having been duly sworn by Eileen Mulvenna,
a Notary Public of the State of New York,
was examined and testified as follows:

EXAMINATION

BY MR. STEPHENS:

Q. Okay. Thank you for being here this morning, Dr. King. My name is Nick Stephens. I'm counsel on behalf of Petitioner, Apple, Inc.

MR. STEPHENS: Would counsel for Patent Owner like to make an appearance?

MR. CANNON: Yes, this is Ted Cannon of Knobbe Martens for Patent Owner, Massimo.

BY MR. STEPHENS:

Q. So we're here today regarding IPR proceeding 2022-01299 regarding U.S. Patent 7,761,127.

Do you understand that, Dr. King?

A. Yes, I do.

Q. And this deposition is being transcribed today. You understand that?

A. Yes.

Q. To ensure a clean record, I'll aim not to interrupt you during your answers. Will you aim to do the same during my questions?

A. Yes.

Q. And if you need a break at any time during the deposition, please feel free to let me know. In general, I'll aim to take a break every hour or so, and then we'll plan to take a lunch break midday.

Does that work for you?

A. Yes. Thank you.

Q. Can you please state your full name?

A. William Paul King.

Q. And can you please state your city of residence?

A. Champaign, Illinois.

Q. You understand that you are under oath for this deposition?

A. Yes, I understand.

Q. And is there any reason that you cannot give truthful and accurate testimony today?

A. There is no reason.

Q. To ensure clarity, I'll define several terms that I'll use throughout the deposition. When I use the terms "Patent Owner" or "Massimo," I'm referring to Massimo Corporation.

Do you understand?

A. Yes.

Q. And when I use the term "Petitioner" or "Apple," I'm referring to Apple, Inc.

Do you understand?

A. Yes.

(Exhibit 1001, US Patent 7,761,127.)

BY MR. STEPHENS:

Q. When I refer to the "'127 patent," I'm referring to U.S. Patent 7,761,127, which is marked as Exhibit 1001 in this proceeding.

Do you understand?

A. Yes.

Q. And when I use the phrase "this IPR" or "this proceeding," I'm referring to IPR 2022-01299.

Do you understand?

A. Yes.

Q. I'll be using the acronym "POSITA" today. And when I do so, I'm referring to a person of ordinary skill in the art at the time of the alleged invention.

You understand?

A. Yes.

(Exhibit 2151, Declaration of William P. King, Ph.D.)

BY MR. STEPHENS:

Q. I may refer to a number of exhibits over the course of the deposition, and I'd just like to index a few of them now.

When I refer to "your declaration" or "the declaration," I'm referring to Exhibit 2151 in this proceeding unless I indicate otherwise.

Do you understand?

A. Yes.

Q. And I'll specifically be referring to the redacted version of your declaration. So I think you can reference either one, but the deposition today will focus on the non-redacted portions of the declaration.

A. Okay. Thank you.

(Exhibit 1004, Yamada Reference.)

BY MR. STEPHENS:

Q. When I refer to "Yamada," I'm referring to Exhibit 1004.

Do you understand?

A. Yes.

(Exhibit 1005, Chadwick Reference.)

BY MR. STEPHENS:

Q. And when I refer to "Chadwick," I'm referring to Exhibit 1005.

Do you understand?

A. Yes.

(Exhibit 1006, Liebowitz Reference, received and marked.)

BY MR. STEPHENS:

Q. When I refer to "Leibowitz," I'm referring to Exhibit 1006.

Do you understand?

A. Yes.

(Exhibit 1007, Cheung Reference.)

BY MR. STEPHENS:

Q. When I refer to "Cheung," I'm referring to Exhibit 1007.

Do you understand?

A. Yes.

(Exhibit 1008, Noguchi Reference.)

BY MR. STEPHENS:

Q. When I refer to "Noguchi," I'm referring to Exhibit 1008.

Do you understand?

A. Yes.

(Exhibit 1014, Scarlett Reference.)

BY MR. STEPHENS:

Q. When I refer to "Scarlett," I'm referring to Exhibit 1014.

Do you understand?

A. Yes.

(Exhibit 2053, Webster Reference.)

BY MR. STEPHENS:

Q. When I refer to "Webster," I'm referring to Exhibit 2053.

Do you understand?

A. Yes.

(Exhibit 2067, Huiku Reference.)

BY MR. STEPHENS:

Q. Finally, when I refer to "Huiku," I'm referring to Exhibit 2067.

Do you understand?

A. Yes, I do.

Q. Can you please describe how you prepared for today's deposition?

A. In preparation for today's deposition, I reviewed my declaration and some of the exhibits, and I met with Mr. Cannon to discuss my declaration.

Q. Approximately how much time did you spend preparing for the deposition today?

A. Referring to the time that I spent since my declaration was completed, perhaps a day or so of work preparing for today.

Q. Who did you work with in preparing to testify today?

A. I worked with Mr. Cannon in preparing to testify today. No one else.

Q. What documents did you review in

preparation for the deposition?

A. I reviewed my declaration. I reviewed portions of the '127 patent, portions of Cheung, Yamada, Noguchi. That's what I recall.

Q. Did you conduct any independent search for material not cited in your declaration in preparation for the deposition?

A. No, I did not.

Q. When were you first contacted to work on this case on behalf of Massimo?

A. I believe that I was contacted in the month of April.

Q. April 2023?

A. April 2023, yes.

Q. And were you aware of Massimo as a company before they contacted you for this proceeding?

A. I had low awareness but some awareness of Massimo and their general business in the area of medical devices.

Q. You had never done any previous work on behalf of Massimo?

A. That's correct.

Q. And when did you first become aware of the '127 patent?

A. When I met with Mr. Cannon for the first time, I became aware of the '127 patent.

Q. And that would have been around April 2023?

A. Yes, I believe April 2023.

Q. Are you aware that the '127 patent has been the subject of an ITC investigation involving the parties in this proceeding?

A. Yes, I am aware.

Q. And had you done any work on behalf of Massimo for the ITC proceeding?

A. No.

Q. Can you please describe the process by which you prepared your declaration?

MR. CANNON: I would just caution the witness to not disclose any conversation or communications with -- with the attorneys, but you may answer the question.

THE WITNESS: The process involved

reviewing the '127 patent, reviewing prior art, including the prior art that you mentioned, Mr. Stephens.

I also reviewed some other technical artifacts and documents that are described in my declaration, including things like textbooks and reference tables and things of that nature.

I also reviewed some of the prior documents from both Apple and from Massimo that were part of the court record.

BY MR. STEPHENS:

Q. Do you recall did those prior documents include any expert declarations submitted in this proceeding before your own?

A. I do not recall. I do not think that I read previous expert declarations before I prepared my own.

Q. Can you approximate what percentage of your declaration you personally wrote versus reviewing words written by someone else?

A. The words in the declaration, all of

those words are my words.

Q. When you say that they're your words, you personally drafted those words?

A. I would say most of the words I personally drafted. All of the words, I -- I edited, reviewed, and included ultimately in my declaration. I'm not sure that I could assign a percentage of the words of what was originally written down simply because the declaration went through many revisions, and I was responsible for the revisions.

Q. Approximately how many hours do you recall spending preparing your declaration?

A. Around -- approximately 60 hours.

Q. In the course of preparing your declaration, did you review the Patent Owner's response that was submitted in this proceeding?

A. I believe that I reviewed some documents from the Patent Owner. Could you refer to a specific document?

Q. One moment. I'm referring to Paper 37, Patent Owner's response to the petition.

A. Yes, I believe I reviewed -- actually, I'm not sure if I reviewed this specific document.

Q. You don't recall whether you reviewed the Patent Owner's response?

A. I would need to --

THE WITNESS: Could you please flip through the document a little bit so I can see some of the content?

(Document review.)

THE WITNESS: Yeah, I apologize, I don't recall if I reviewed this specific document or not.

MR. STEPHENS: Okay. That's fine. You can take that document down.

THE WITNESS: Is that document referred to in my declaration?

BY MR. STEPHENS:

Q. I do not believe so.

A. Okay.

Q. In preparing your declaration, did you communicate in any way with any of the named inventors on the '127 patent?

A. I had no communication with the named inventors.

Q. And to be specific, did you ever communicate with Mohamed Diab?

A. I did not communicate with Mohamed Diab.

Q. Did you communicate with anyone besides Patent Owner's attorneys in preparing your declaration?

A. Yes, I did. I had one conversation with a Massimo employee who was responsible for software development, and we had a discussion about some of the source code.

Q. And besides that Massimo employee, do you recall anyone else that you communicated with in connection with preparation of your declaration?

A. In addition to Mr. Cannon, there was one other attorney that -- that attended one meeting, and that was it.

Q. I'll refer to your declaration, paragraph 3. And here you provide a table that contains a list of documents that you indicate you had reviewed and considered in conducting the analysis in forming the opinions set forth in the declaration; is that right?

A. Yes.

Q. Is this a comprehensive list of documents that you reviewed?

A. I believe it is, yes.

Q. Do you recall considering any other documents not identified in this table in preparing the declaration?

A. There were a few cases where I was evaluating the most appropriate references to include. I believe I consulted one or two heat transfer textbooks that are not included in the list, but I ultimately did not use those. I chose the ones that are presented in the declaration instead.

I think the same is true for the material property reference tables that I cite in the declaration. I think in those cases I also looked at some alternative options, ultimately did not use those. I used the ones that are reported here in the declaration.

Q. And do you recall why you selected the ones that are cited in the declaration versus the other ones that you reviewed?

MR. CANNON: Objection, calls for the expert's mental impressions. I instruct the witness not to answer.

MR. STEPHENS: Counsel, I believe the only basis for instructing the witness not to answer would be for privilege. Are you contending that it's privileged?

MR. CANNON: Yes, it's under the work product of the expert and his mental impressions in making decisions outside of the scope of the actual declaration and his opinions.

BY MR. STEPHENS:

Q. Dr. King, do you recall what the other textbooks were that you reviewed that are not cited in your declaration?

A. I do not recall. In fact, in one case, I do recall one. There was a heat transfer textbook that was a different edition of the heat transfer textbook that I do cite. So it was just a different edition from a different year, but substantially the same content.

Q. In forming your opinions in this proceeding, did you rely on any assumptions that are not identified in your declaration?

A. No.

Q. Have any of your opinions changed since the time that you signed your declaration regarding the '127 patent?

A. My opinions have not changed since the time that I signed the declaration.

Q. And are you aware of any errors that exist in your declaration?

A. I am not aware of any errors that exist.

Q. Are you aware of any typos that might exist in your declaration?

A. I'm not aware of any typos.

Q. In your career, approximately how many times have you been retained as an expert in litigation matters?

A. Approximately three times.

Q. Including this proceeding?

A. Including this proceeding.

Q. And in the prior two instances, were they patent cases as well?

A. Yes.

Q. Were they in the context of an IPR or a different proceeding -- type of proceeding?

A. Different type of proceeding.

Q. Would that be a district court litigation?

A. Yes.

Q. Do you recall how many times you have been deposed as an expert in litigation matters?

A. Including today, one.

Q. Okay. Well, welcome.

A. Thank you.

Q. Before -- strike that.

In Table -- in paragraph 3 of your declaration, you indicate that you had reviewed Exhibit 1003, which is the declaration of Brian

Anthony; correct?

A. Yes.

Q. And before reviewing Dr. Anthony's declaration, were you aware of Dr. Anthony?

A. No, I was not.

Q. You had never worked with or against Dr. Anthony?

A. No.

Q. Is your compensation for your work on this case in any way contingent on any other factor other than the number of hours that you work on the case?

A. No, it's not.

Q. Is your compensation dependent on the outcome of this case or the substance of your opinions?

A. No, it's not.

Q. Has a court ever precluded you from offering an opinion in a litigation matter?

A. No.

Q. Have any of your opinions previously been criticized by a court?

A. No.

Q. I'd like to turn to paragraph 4 of your declaration.

In paragraph 4, you indicate that you are currently the Professor and Andersen Chair in the Department of Mechanical Science and Engineering at the University of Illinois Urbana-Champaign.

Is that still correct?

A. Yes.

Q. And you hold academic appointments in the Departments of Electrical and Computer Engineering and Materials Science and Engineering, as well as the Department of Biomedical and Translational Biosciences in the Carle Illinois College of Medicine.

Is that still correct?

A. Yes, that's correct.

Q. And can you tell me a little bit about the mission of the Department of Biomedical and Translational Biosciences?

A. I can. So --

Q. Go ahead. Thank you.

A. The Carle Illinois College of Medicine describes itself as the first engineering-based College of Medicine in the United States. So it's a partnership between Carle Hospital and the College of Engineering at University of Illinois Urbana-Champaign.

The Department of Biomedical and Translational Biosciences is one of, I believe, two departments in the Carle Illinois College of Medicine. And the Department of Biomedical and Translational Biosciences really focuses on the technology aspects of medicine, so technology referring to tools and methods that apply science for advancing the field of medicine.

Q. And what is your role in the Department of Biomedical and Translational Biosciences?

A. I hold an affiliate appointment in that department, as I do in the Departments of Electrical and Computer Engineering and the Department of Material Sciences and Engineering. So an affiliate appointment has some responsibilities and privileges that are different from the regular faculty appointment that I hold in the Department of Mechanical Science and Engineering.

So as an affiliate professor of biomedical and translational biosciences, I'm invited to participate in events and activities of the department. I may advise students or teach courses, serve on committees and otherwise help govern the department in an affiliate manner where I would be invited to do those things on a part-time basis rather than kind of my full-time responsibilities in mechanical engineering.

Q. Outside of this proceeding, do you have experience with photoplethysmography, PPG, devices, such as pulse oximeters?

A. No, I do not.

Q. And outside of this proceeding, do you have experience designing, researching, or building heat sinks for electronic devices?

A. Yes, I do.

Q. Can you describe some of that experience?

A. I've been working on thermal management and heat sinks for more than 20 years. Currently, I have projects going on in my research group at the university associated with thermal management, removing heat, designing heat sinks related to power electronic devices, systems that are designed for electrification such as fast charging of electric vehicles, for example.

That work involves both experiments and simulations, material selection, design, testing, a host of engineering matters. So I'm currently advising four or five students at least that are actively working on projects in this area. I would say over the last 20 years, I've advised more than a dozen students and projects in this topic area.

Q. So you do not have experience with thermal management in PPG devices before this proceeding; is that correct?

A. I do not have experience in pulse oximetry devices before this proceeding.

Q. And pulse oximetry devices, would that more broadly encompass optical probes for PPG devices more generally, or is it specifically pulse oximetry for detection of oxygen saturation?

A. I do have experience with optical probes, using optical probes to measure physical parameters, measure thermal and electrical parameters. I have experience in designing thermal systems that are used for thermal management related to optical systems and optical measurements.

Q. In paragraph 6 of your declaration, you indicate that you have more than 20 years experience teaching university-level courses in heat transfer, thermal dynamics, and product design; correct?

A. Correct.

Q. So in these decades of experience, have you ever been made aware of a device that estimated the temperature of electronic components based on a signal from a temperature sensor thermally coupled to a heat sink?

A. Yes.

Q. Is that a common practice in your

experience?

A. It is common to attach temperature sensors to heat sinks, yes.

Q. And is it common to estimate the temperature of other electronic components thermally coupled to the heat sink?

A. It is common to use temperature measurements within an electronic system combined with other information to estimate the operating temperature of electronic components.

Q. And what are some reasons that an engineer might be interested in estimating the operating temperature of electronic components?

A. Electronic components that operate at a temperature that is -- that operate at a high temperature, they can have shortened lifetimes. They can fail early. They may lose their accuracy or their ability to function correctly in some cases.

Q. When you say that the electronic components may lose accuracy, would that include LEDs in your experience?

A. When I said that the electronics -- electronic components may lose accuracy, I was thinking of sensors that would measure some physical parameter and report the physical parameter through an electronic signal, like a voltage or a resistance. And so the measurement of the physical parameter, the accuracy of that measurement may be affected by the operating temperature of the device. An LED is not a sensor.

Q. Do you have experience estimating the operating temperatures of LEDs in an electronic device?

A. Yes, I do.

Q. Can you describe some of that experience?

A. So I worked on projects where there were LEDs and other heat generating devices that were mounted on circuit boards, and the temperature of the LEDs would be measured using different methods, for example, infrared thermometry, for example.

Q. Are you aware of any other methods for estimating LED operating temperatures?

A. I am aware, yes, of other methods for estimating LED operating temperatures.

Q. Are you aware of any prior approaches for estimating the operating temperatures of a group of LEDs using a single temperature sensor?

A. I am not, no.

Q. Have you -- are you aware of any approaches for estimating LED operating temperatures by measuring a temperature of a heat sink thermally coupled to the LED?

A. I am not aware, no.

Q. Did you search for any prior art that might disclose that concept as you prepared your declaration?

A. One of the references that I provide in my declaration, I believe it's Design of Heat Sinks [sic] by Kraus, I reviewed that textbook. And in my review of the textbook, I did not find LEDs mounted on a heat sink and a temperature sensor measuring the LED temperature through the heat sink. I did not find that.

Q. Do you have any personal experience outside of this proceeding with devices configured to compensate for temperature-induced wavelength shifts in LEDs?

A. No, I do not.

Q. Do you have any personal experience with devices that include a thermal core in a printed circuit board?

A. Yes, I have some experience.

Q. Can you describe that experience?

A. I have evaluated candidate technologies for printed circuit board manufacturing that allows for the distribution of metal within a circuit board or -- to configure metal objects around the circuit board. So I think that's responsive to your question. One of the purposes of such metal distribution within a circuit board could be for thermal management.

Q. What do you mean by "thermal management"?

A. Thermal management in this sense refers to either providing a heat removal function or a temperature management function through engineered heat transfer pathways.

Q. And what materials would the thermal core typically be made from?

A. So the materials that I am thinking of for the technologies that I'm familiar with, there may be copper distributed around or within a circuit board that could provide a thermal management function.

Q. And can you design the thermal core to achieve a desired thermal management function?

A. Yeah, the phrase "thermal core" does not have a rigorous, well-accepted definition in heat transfer science and engineering. So we can use the phrase, but it would mean different things in different circumstances.

It is possible to arrange different materials of different properties, thermal properties, different geometries, it's possible to arrange those in a way that could provide a thermal management function, such as heat removal or achieving desired temperatures.

Does that answer your question?

Q. No, that's helpful.

In your experience, have you ever measured a temperature of a thermal core in a PCB?

A. I have measured the temperature -- I've used temperature sensors in infrared measurements to measure the temperature on circuit boards and on devices that are mounted on circuit boards. We would have to, I think, define what we meant by "thermal core" in order to go deeper than that about thermal core temperature measurements.

Q. I think for the purpose of this question, I would define a "thermal core" as the metallized portion of the PCB designed to perform the thermal management function.

A. So if for the purpose of the question we say that the portion of the PCB that consists of metal that may provide a thermal management function, yes, I believe I've measured the temperature of such a thermal core.

Q. Have you used that temperature measurement to estimate the operating temperatures of electronic components thermally coupled to the thermal core?

A. I have used temperature measurements on circuit boards as one piece of information among others that -- that could be used to calculate the temperature of an electronic device. So those types of estimations require other sources of information, including how the heat generating device is connected to the circuit board, the distribution of materials and their properties, and very importantly, the thermal connectivity between all of those elements and their environment or other aspects of the system.

So the temperature measurement is one of many pieces of information that one would require to estimate the temperature of the electronic device.

Q. All right. Why don't we turn to Exhibit 1001, the '127 patent.

A. I have it up.

Q. And let's turn to Figure 12, please.

Did you review Figure 12 in the course

of preparing your declaration?

A. I believe that Figure 12 or something very similar to it is in my declaration.

Q. What's your understanding of what's shown in Figure 12?

A. This -- perhaps we can turn to my declaration.

Q. Is there a particular portion of the declaration?

A. Give me a moment to find it, please.

For example, around paragraph 60.

Q. Okay. Go ahead, Dr. King.

A. So I address the heat transfer pathways and the operation described in Figure 12. I address this actually at multiple places in my declaration. So I'll briefly summarize some of the key aspects here.

So we have the LED devices. They emit light, shown on the images, optical radiation. They also get hot. So they generate some heat. The heat from the LEDs flows out of the LEDs by radiation, conduction, and convection. So radiation to the nearby environment, convection to the nearby air, and conduction to the nearby air and also into the thermal mass shown in the diagram.

So some of the heat that flows into the thermal mass flows into the temperature sensor. Some of the heat also flows away into the other parts of the system by thermal conduction. The temperature sensor is affixed to the thermal mass and is measuring the temperature of the thermal mass in the location to which it's attached.

Q. And is the primary heat transfer mechanism of thermal energy from the light emitter 710 to the temperature sensor 1230 via the thermal mass 1220 conduction?

A. It's actually not possible to understand that from the diagram, but I believe it's very safe to assume that conduction is an important heat transfer mechanism here.

Q. And Figure 12 shows a block labeled 710 referred to as "Light Emitters."

You see that?

A. Yes.

Q. Is it your understanding that the light emitters 710 could be LEDs?

A. Yes.

Q. And Figure 12 indicates that there could be one, two, all the way to n light emitters; is that correct?

A. Yes.

Q. So the '127 patent does not restrict the number of light emitters 1210 that could be thermally coupled to the thermal mass; is that right?

A. This diagram shows that there could be one or multiple light emitters.

Q. And the multiple could be two, for example?

A. Yes.

Q. It could alternatively be three, four, or more?

A. Yes.

Q. And does this diagram accurately represent the relative position of the light emitters 710 relative to the temperature sensor

1230?

A. I'm sorry that I don't understand the question. What do you mean by "accurately represent"?

Q. Does the '127 patent require the temperature sensor 1230 to be positioned opposite the light emitters 710 on the thermal mass?

A. I do not recall the positioning in the claims. We can go look at the patent to see.

So looking at -- Claim 1 requires that the temperature sensor thermally coupled to the thermal mass. Claim 7 has the same. So those two claims -- neither of those claims require that the temperature sensor is on the opposite side.

Q. Does Figure 12 indicate that it would be suitable to position the temperature sensor on the opposite side of the thermal mass in some implementations?

A. I would not take that away from Figure 12. I think Figure 12 is more conceptual, showing the general relationship of some of the elements of the system. The location of the temperature sensor -- the best location for the temperature sensor or an effective location for the temperature sensor, in order to determine that it requires more information that's available in Figure 12.

So Figure 12 doesn't tell you enough to know, you know, the best location or appropriate locations for the temperature sensor relative to the thermal mass and the light emitters, only that they have some communication with each other and the relative flow of the thermal energy here.

Q. Would a POSITA know how to select an appropriate location for the temperature sensor?

A. In order to perform what task?

Q. The tasks described for the thermal mass in the '127 specification.

A. So the '127 patent describes the function of a thermal mass -- the presence of a thermal mass.

The -- let's go to my declaration. Excuse me while I find what I'm looking for.

Q. Please, just let me know once you find it.

A. Thank you.

(Pause.)

THE WITNESS: So the -- could you please reask your question? I'm ready to answer.

BY MR. STEPHENS:

Q. Would a POSITA know how to select an appropriate location for the temperature sensor 1230 in order to perform -- achieve the functions of the device disclosed in the '127 patent?

A. So the selection of the temperature sensor and its location and its operation is one of many mechanical design and heat transfer calculations that one would have to do to design such a system. So the system has the LEDs that are generating heat. The heat flows into the thermal mass.

The function of the thermal mass will -- the specific performance of the thermal mass will depend upon the location of the LEDs and how much heat they're generating and the frequency that they operate at, also how the thermal mass is thermally coupled to other elements of the system and the environment and so on.

So the location and operation of the temperature sensor is -- would require engineering work to solve kind of the system-level problem that has many factors that would be part of it.

Q. Would the engineering work that would be required be within the skill of a POSITA?

A. Well, certainly after reading the '127 patent, a person would have enough information to do that engineering work and design a system.

Q. Can you point me to that information that would allow a POSITA to do that?

MR. CANNON: Objection, beyond the scope.

BY MR. STEPHENS:

Q. You may proceed, Dr. King.

A. Yeah, I would not refer to any specific line or paragraph, but rather taking the entire -- entirety of the '127 specification, all of the aspects that are described therein.

Q. So sitting here today, you are unable to point to anything in the specification of the '127 patent that would tell a POSITA how to select an appropriate location for the temperature sensor?

MR. CANNON: Objection, beyond the scope.

THE WITNESS: Yeah, I wouldn't say that. I would say that upon reading the '127 patent, a POSITA would have a good idea about how to proceed to design a system that had a correct location for the temperature sensor and the thermal mass and the other key engineering choices that one would need to make to design an effective system.

BY MR. STEPHENS:

Q. Did you review the '127 patent in the course of preparing your declaration?

A. Yes, I did.

Q. So you indicated that a POSITA would have a good idea -- strike that.

You indicated that upon reading the '127 patent, a POSITA would have a good idea about how to proceed to design a system that had a correct location for the temperature sensor and the thermal mass.

Did I appropriately quote you there?

A. Yes, you did.

Q. So I would like to understand what from the '127 specification would have given a POSITA a good idea about how to proceed to design a system that had a correct location for the temperature sensor.

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: The engineering work required to design a system described in the '127 patent could start -- would start with an understanding of what's in the '127 patent and also the technical background that would make a person a POSITA, plus additional engineering work that would involve design and testing either through computational simulations or prototyping or both and further engineering analysis.

So in order to achieve the results of the '127 patent in a real product or system, one would need to do all of those things. In reviewing the '127 patent, it discloses the elements and their combination that would be helpful in achieving that goal.

BY MR. STEPHENS:

Q. Would it require an extraordinary amount of experimentation for a POSITA to select an appropriate location for the temperature sensor to achieve the thermal functions disclosed in the '127 patent?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: It would require real engineering work with either computational numerical experiments done with simulations and/or other engineering analysis and/or prototyping. So I can't speak to what "extensive" would mean, but it would be a substantial engineering project to get it right.

BY MR. STEPHENS:

Q. Could we refer to Columns 10 and 11 of the '127 patent.

Just let me know when you've arrived at that portion of the '127 patent.

A. Okay.

Q. Based on your review of the '127 patent, do you see anything in Columns 10 or 11 that would inform a POSITA how to select an appropriate location for the temperature sensor?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: So your question is about para- -- I'm sorry, Columns 10, 11, and 12; is that right?

BY MR. STEPHENS:

Q. We can just limit it to Columns 10 and 11.

A. Okay.

(Document review.)

THE WITNESS: Okay. I've reviewed those two columns. Would you please ask your question again?

BY MR. STEPHENS:

Q. Based on your review of those two columns, is there anything that you saw in these two columns that instructs a POSITA how to select an appropriate location for the temperature sensor?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: So in these columns, there are some examples of where things may get placed and examples of some materials. And then there's also just a general description about how the elements could be configured relative to each other.

So with this information and with the expertise of a POSITA and some additional engineering work, it would be possible to -- to design a system, you know, described in the '127 patent. There are some engineering steps and tasks that are required in order to perform that design work that are not reported in these columns.

BY MR. STEPHENS:

Q. Would those extra steps that would be required to select an appropriate location for the temperature sensor --

MR. CANNON: Objection, beyond the scope, relevance.

MR. STEPHENS: Excuse me, Counsel. I wasn't finished with my question.

BY MR. STEPHENS:

Q. Would those extra steps that would be required to select an appropriate location for the temperature sensor be within the skill of a POSITA?

A. Yes. And they would involve some form of testing.

Q. I'd like to turn to Figure 14.

And did you review Figure 14 in the course of preparing your declaration?

A. Yes, I did.

Q. And would you agree that Figure 14 depicts a series of inner layers, 1402, 1403, 1404, and 1405, that collectively provide a thermal mass 1220 within the substrate?

A. The figure does have the inner layers. There are also some unlabeled inner layers marked by diagonal hashmarks.

Q. What is your understanding of those layers that are marked by diagonal hashmarks?

A. I believe the diagram conceptually represents that there's at least two different materials that are included in the layers. So the diagonal hashmark layer is a different material than the labeled layer.

Q. And I refer to Column 11, lines 10 through 12.

A. I'm sorry, which column?

Q. That's Column 11, lines 10 through 12.

A. Uh-huh.

Q. And that reads, "The inner layers 1402 to 1405, e.g. inner layers 1402 (Figure 18), have substantial metallized areas 1411 that provide a thermal mass 1220 [sic]..."

Do you see that?

A. Yes, I do.

Q. Do you have an understanding of the

thermal function of inner layers 1402 through 1405?

A. Yes, I do.

Q. Can you describe that function?

A. In a design where the labeled layers are a metal, they provide -- they have higher thermal conductivity than the surrounding layers which may -- let me strike that.

So in an embodiment where we have alternating layers of a high thermal conductivity metal and a second material of lower thermal conductivity, the layer structure will promote lateral heat transfer and resist heat transfer in the normal direction. That would be the vertical direction in this figure.

Q. In the embodiment depicted in Figure 14, the thermal mass is comprised of a series of layers; correct?

A. Give me one moment, please.

Q. And while you're looking at that, I'll just note maybe in five minutes, we can take a break, if that works for you.

A. Yes, please. Thanks.

(Document review.)

THE WITNESS: So I'd like to start with the board's definition of "thermal mass," which is a mass having resistance to temperature change on a scale relevant to estimating LED wavelengths. And the '127 patent uses the phrase "thermal mass" several places, but also implies its function many other places.

So in this figure, I do not disagree that the -- this particular location in the '127 patent refers to those layers as "thermal mass," but I believe that the definition of "thermal mass" is much broader than that. And, in fact, using the board's definition of "thermal mass" with this diagram, we could identify actually quite a few different instances of thermal mass even in this one diagram.

BY MR. STEPHENS:

Q. Okay. Can you explain that? What are the instances of the thermal mass depicted in this diagram?

A. So, again, "thermal mass" is defined by its function to resist temperature change on a scale relevant to estimating LEDs at wavelengths rather than its geometry. However, taking the '127 patent as a whole and understanding having analyzed the heat transfer in the system, the thermal mass could, for example, be layers three and four and the materials on either side of it. For example, that could be a thermal mass. Or the thermal mass could also comprise layer two in addition to those other layers, for example.

Q. And could the thermal mass comprise just a single metallized layer?

A. The definition of "thermal mass" is based on its function to provide resistance to temperature change on a scale relevant to estimating LED wavelengths. So any mass that met that definition would be a thermal mass.

Q. So it would be possible for a single sheet of metal to be designed to perform the function of the thermal mass disclosed in the '127 patent?

A. It would be possible to have a single sheet of metal that resisted temperature on a scale relevant for estimating LED wavelengths.

Q. What would be some suitable metals that could achieve that function?

A. So the main design criteria for the metals that might be included in the thermal mass would be the thermal properties. So high thermal conductivity, high heat capacity. So we would also want to consider manufacturability, as well as cost or other engineering factors that are commonly assessed here.

But in my declaration, I discuss both copper and aluminum, which are common metals that meet those criteria and are commonly used in electronic systems.

Q. So two important considerations for the selection of a material for the thermal mass would be thermal conductivity and heat capacity?

A. Among others, yes.

MR. STEPHENS: Okay. Why don't we

take a break, and we'll come back to those concepts after the break.

THE WITNESS: Thank you.

MR. STEPHENS: How about ten minutes?

THE WITNESS: Okay.

MR. CANNON: Okay.

MR. STEPHENS: Okay. Thanks.

(Recess from the record.)

MR. STEPHENS: Back on the record.

THE REPORTER: We're back.

BY MR. STEPHENS:

Q.   Dr. King, did you discuss the substance of your testimony with counsel during the break?

A.   No.

Q.   All right. Before we broke, I had asked two important considerations for the selection of a material for the thermal mass would be thermal conductivity and heat capacity. And you responded, among others, yes.

Do you recall that?

A.   Yes.

Q. Can you describe the difference between thermal conductivity and heat capacity?

A. So both thermal conductivity and heat capacity are properties of materials. Every material has a thermal conductivity, and every material has a heat capacity. Thermal conductivity refers to how much heat will pass through a material for a given temperature difference. Heat transfer requires a temperature difference between two locations within an object. So it's that temperature difference that provides the potential for energy to flow in the form of heat. And so thermal conductivity is a proportionality constant between that temperature difference and the quantity of heat that flows.

Heat capacity refers to the thermal energy storage ability of a material. When I put thermal energy into a material, its internal energy will increase. Its temperature will increase. And so heat capacity is a proportional constant between the quantity of heat that flows into or out of an object and the temperature change that occurs due to that energy flow.

Q. Are thermal conductivity -- strike that.

Is thermal conductivity an intrinsic property of a material?

A. Thermal conductivity is an intrinsic property of a material.

Q. And when I refer to an intrinsic property, what do you understand that to mean?

A. Intrinsic property is a property that is constant regardless of the quantity of the material. So thermal conductivity is constant independent of the quantity of material with exceptions only in extreme environments that are not relevant to the '127 patent.

Q. Is heat capacity an intrinsic property of a material?

A. Heat capacity is also an intrinsic property. Heat capacity of a substance is not a function of the quantity of the substance, again except in extreme circumstances in situations that are not relevant to the '127 patent.

Q. When you refer to heat capacity, is there a distinction between heat capacity and specific heat capacity?

A. So heat capacity -- thank you for asking that question.

So heat capacity is commonly used to refer to the specific heat capacity, which is an intrinsic property. Heat capacity can also in some cases be informally used to refer to the product of the heat capacity and the mass.

Q. So in that context, if we were distinguishing heat capacity from specific heat capacity, specific heat capacity would be an intrinsic property of a material, and heat capacity would be an extrinsic property?

A. Yes, that is correct.

Q. Do you teach any under- -- or have you teached [sic] any undergraduate courses that review the concepts of thermal conductivity and heat capacity?

A. I have taught undergraduate and graduate courses both that review these concepts.

Q. Which courses would you commonly teach these concepts in an undergraduate course?

A. They would commonly be taught in an undergraduate course in heat transfer. Most mechanical engineering undergraduate programs in the United States require one course on heat transfer.

Q. Would you expect that a student who passed one of your heat transfer undergraduate courses would be able to determine the thermal conductivity and heat capacity of a sheet of metal?

A. I would expect a student who passed the course to understand those concepts, to be able to perform a material selection exercise by looking up those properties in a table of materials as part of a design exercise. I would expect them to have a sufficient understanding of heat transfer principles so that they would be able to understand the operation of a piece of equipment or a method for measuring thermal conductivity or heat capacity.

Q. And earlier you mentioned that in the '127 patent, a "thermal mass" is defined not by its geometry but by its thermal function; is that correct?

A. The definition of "thermal mass" relies on resisting temperature change relevant for estimating LED wavelengths.

Q. And two of the important considerations in designing the thermal mass for that thermal function would be thermal conductivity and heat capacity; correct?

A. Those are two of many considerations that would need to be made in designing a thermal mass.

Q. I'd like to refer to Figure 14 of the '127 patent again.

And I think that earlier we established that one or more of these inner layers, 1402, 1403, 1404, 1405, could be designed to function as a thermal mass; is that correct?

A. Yes, that's correct.

Q. And what factors would a POSITA need to consider in designing one or more of these layers to serve as a thermal mass?

A. When I look at Figure 14, what strikes me the most is how much of the thermal function relies upon things that are not in this diagram. So we need to consider how the thermal mass and the objects around it are thermally connected to the environment, what else is going on in the system, where are the LEDs or other heat sources that may exist in the system, where is the temperature sensor, what are the heat transfer modes.

So within the diagram, we also care about the geometry and location of the different elements, their thermal and mechanical properties, how they've been affixed to each other and what the implications are for thermal coupling between the different elements; for example, is there a thermal resistance that exists between layers that's not shown on the figure, things of that nature.

Q. Would a POSITA also need to consider the size of the layers?

A. A POSITA would need to consider, among other factors, the geometry of the layers, including the thickness, their width, the dimension into the page here, the distance between the adjacent layers, how the layers are affixed to each other, and so on.

Q. Does the '127 patent specification provide specific dimensions for the layers shown in Figure 14?

A. I do not recall that the '127 patent provides thicknesses.

Q. Would a -- would a POSITA understand how to dimension the layers shown in Figure 14 to achieve the thermal function of a thermal mass?

MR. CANNON: Objection, beyond the scope and relevance.

BY MR. STEPHENS:

Q. You may proceed, Dr. King.

A. Yeah, the -- the steps required to design the thermal mass include an analysis of the elements that are present in Figure 14 or alternatives, as well as an analysis of the surrounding system, the sources of heat generation, where the temperature sensor might be located, how the thermal mass and other parts of the system are thermally coupled to the environment and other parts of the system.

A POSITA would go through an engineering analysis that included all of those things. It would consist of some engineering analysis, probably some modeling, testing with numerical experiments, computations in a computer possibly with prototyping.

In this particular embodiment of a thermal mass that has these inner leafed layers, a POSITA could consider the layer thickness and material selection as part of that comprehensive process.

Q. Based on your review, does the '127 patent specification expressly describe how to perform the type of engineering analysis modeling and testing that would be needed to design the thermal mass to perform the thermal function described in the patent?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: The '127 patent describes the function of the thermal mass and how it operates in the system, and it provides some illustrative examples and embodiments. And in a few cases, it provides some specific material -- candidate materials and so on.

In my opinion, a POSITA would be able to read the '127 patent and then, in combination with their engineering experience, be able to go through an exercise where they could design a system that met the description of the '127 patent.

BY MR. STEPHENS:

Q. So a POSITA would understand how to design the thermal mass to perform the requisite thermal function even without all of the details regarding dimensions, materials provided expressly in the specification?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: A POSITA would be able to read the '127 patent and combine it with their own expertise to perform all of the engineering tasks required to realize the invention described in the '127 patent.

BY MR. STEPHENS:

Q. And that would include selecting, for example, an appropriate material for the thermal mass; correct?

A. Material selection would be one of many steps that would be required in that engineering work flow.

Q. Would that further include, for example, determining the appropriate geometry for the thermal mass?

A. Determining the geometry of the metal layers and the elements, the composition, the geometry of the thermal mass, all of those things would be part of the overall engineering task, yes.

Q. The overall engineering task that a POSITA would know how to do, given the function of the thermal mass described in the '127 patent?

A. A POSITA would be able to read the '127 patent and combine it with their own experience and then perform additional engineering tasks to design the invention described in the '127 patent.

Q. Okay. I'd like to turn to Columns 10 and 11 again of the '127 patent.

And all the way at the bottom of Column 10, starting at line 67, it reads, "The substrate 1200 is also configured with a relatively significant thermal mass, which stabilizes and normalizes the bulk temperature so that the thermistor measurement of both temperatures is meaningful."

Do you see that?

A. Yes, I see that.

Q. Would you agree that the function of the thermal mass in this description is to stabilize and normalize the bulk temperature?

A. So the board's definition of "thermal mass" is to provide the function of resisting temperature change on a scale that's relevant for estimating LED wavelengths. So within the context of this specific sentence, the stabilizing and normalizing is -- contributes to the function of the thermal mass.

Q. What's your understanding of what it

means to stabilize the bulk temperature?

A. So I read stabilize and normalize together. So the stabilization aspect, I believe refers to the aspect of thermal mass that reduces the high frequency fluctuations of the LEDs rapidly turning on and off. So if the thermistor were to sense those high frequency fluctuations, it would not be able to make an accurate temperature measurement.

Q. Is that specifically with respect to the stabilization aspect, or does that also encompass your understanding of normalization?

A. I take the phrase "stabilize" and "normalize" altogether.

Q. What thermal properties of the thermal mass allow it to stabilize and normalize the bulk temperature?

A. Hmm. So the "stabilize" and "normalize" function relies upon the thermal properties of the thermal mass, but also the geometry of thermal mass and any constituent components, as well as the thermal coupling of the thermal mass with the LEDs and the temperature sensor, the thermal environment, other elements that may be in the system.

Q. Does heat capacity play a role in the stabilization and normalization of the bulk temperature?

A. Heat capacity and thermal conductivity play a role in the stabilization and normalization.

Q. Can you explain how that is?

A. In my declaration, I have some discussion on the concept of thermal time constant, which I think is helpful here. So thermal time constant is a well-known concept in heat transfer, science and engineering, and it refers to how rapidly an object's temperature will change in response to -- to a heat flow. So an object with a small thermal time constant will have rapid temperature fluctuations or rapid temperature responses to a heat input. An object with a high thermal time constant will take longer for the temperature to change in response to a heat flow.

Q. How does the thermal time constant

relate to thermal conductivity or heat capacity?

A. Generally, a thermal time constant is proportional to heat capacity. So a higher heat capacity results in a proportionally higher time constant. So that's generally true, although not always true.

The thermal time constant, however, depends upon many more factors than just the heat capacity. The thermal time constant depends upon how the object in question is connected or thermally coupled to surrounding objects or to its environments. So the heat capacity, while important, is not determinative of a thermal time constant.

And, sorry, you also asked, I believe, about how thermal conductivity matters. So thermal conductivity is relevant to thermal time constant in at least two ways.

First, thermal conductivity may affect how heat flows into or out of an object. So an object with high thermal conductivity heat will easily flow in or out, and that would contribute to a lower thermal time constant.

An object with a low thermal conductivity would resist heat flow into or out of the object, contributing to a higher thermal time constant. The thermal conductivity also matters in terms of how the object is connected to its environment. So the thermal conductivity may also play a role in that regard, as well.

Q. Referring back to the sentence we just looked at in the bottom of Column 10 to the top of Column 11 of the '127 patent, again, that refers to "The substrate 1200 is also configured with a relatively significant thermal mass..."

Why is a relatively significant thermal mass needed to stabilize and normalize the bulk temperature?

A. So the phrase "thermal" does not have a standard rigorous definition that's well known in heat transfer science and engineering. So if we're going to talk about a thermal mass, we need to understand -- you know, discuss it or understand it in the context of a specific function or application, operation, concept.

And so I think that the inventors here use the word "significant" just to indicate that the thermal mass has a meaningful participation in the heat transfer in the system.

Q. And by "meaningful participation," can you elaborate on what that means?

A. Well, the board's definition is to provide resistance to temperature change on a scale relevant to estimating LED wavelengths. So I think the words "meaningful" and "relevant" here are consistent. For the thermal mass to have meaningful participation, it's resisting temperature on a scale relevant for the LED wavelength estimation. If it was on an irrelevant scale, then the -- we could perhaps drop the word "significant."

Q. So you understand that the words "relatively significant" modify the term "thermal mass" in this sentence at Column 11, line 1 of the '127 patent; correct?

A. My read is that the words "relatively significant" indicate that the thermal mass has a meaningful effect on the thermal operation of the system.

Q. But the sentence itself uses the words "relatively significant" to describe an appropriate or suitable thermal mass; is that correct?

A. I think reading the '127 patent in its entirety, the "thermal mass" definition is consistent with the board's definition providing resistance to temperature change on a scale relevant to estimating LED wavelengths.

Q. But a thermal mass -- strike that.

Does the '127 patent define specific bounds for a relatively significant thermal mass?

A. The '127 patent talks about the function of the thermal mass in providing a heat transfer pathway between the LEDs and the temperature sensor and in that the thermal mass allows the temperature sensor to make a relevant and meaningful measurement.

Q. Based on your review of the '127 patent, it does not restrict the number of LEDs that could be mounted on the substrate and thermally coupled to a thermal mass; correct?

A. If there were any restriction on the number of LEDs, it would be that in some case, perhaps the number of LEDs would prevent a device from meeting the definition of "thermal mass," somehow prevent a single temperature sensor from obtaining a representative temperature measurement. So there may be some restriction through implication or the function of the device; but otherwise, the number is not restricted, is my understanding.

Q. Would a POSITA reviewing the specification of the '127 patent know how to design the thermal mass to accommodate different numbers of LEDs?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: I think that the steps that I described previously to read and understand the '127 patent, to have a POSITA with the required, you know, experience and background, going through all of the engineering steps that I described, and the testing as well, I believe that that collection would result in, you know, successful designs that were independent of the number of LEDs.

BY MR. STEPHENS:

Q. A POSITA would know how to achieve a successful design independent of the number of LEDs?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: I believe that a POSITA could read the '127 patent and go through the engineering tasks that I described and design a successful device or system that met the limitations of the '127 patent that used multiple LEDs.

BY MR. STEPHENS:

Q. But just to confirm, is your answer yes, a POSITA would know how to achieve a successful design independent of the number of LEDs?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: A POSITA could read and

understand the '127 patent, go through the engineering tasks that I described, and successfully design a system that met the limitations of the '127 patent, that system having multiple LEDs.

BY MR. STEPHENS:

Q. And applying that process that you've just referenced, a POSA could successfully design a thermal mass to accommodate different positions of LEDs on the substrate; correct?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: The design process requires design choices and engineering work on more than just the thermal mass, also involves the -- how the thermal mass is coupled to other elements in the system and the thermal environment and the operating conditions of the LEDs and many other aspects.

BY MR. STEPHENS:

Q. And those are design choices and

tradeoffs that a POSITA would know how to implement; correct?

A. A POSITA would be able to read and understand the '127 patent and go through a systems engineering approach to make all of the required engineering design choices and tradeoffs associated with the thermal mass and the other aspects of the system.

Q. Is it your understanding that in a device that includes multiple LEDs, that the LEDs may be activated at different times and for different lengths of time?

A. A device that has multiple LEDs could have different operating frequencies, different duty cycles, different power profiles, which is a way of referring to how the heat dissipated into the substrate varies as a function of time. So all of those things could be different for different LEDs.

Q. And a POSITA would know how to accommodate those differences in the design of a thermal mass; correct?

MR. CANNON: Objection, beyond the

scope and relevance.

THE WITNESS: The analysis of the heat transfer in the system when we have multiple LEDs, each with different operating conditions, frequency, duty cycle, power profile, and so on, this is a challenging engineering task.

So a POSITA would spend some time doing analysis and testing in order to make all of the correct choices at the system level and also the locations of the LEDs, the thermal mass, the thermistor, and so on.

BY MR. STEPHENS:

Q. But the specification of the '127 patent leaves those choices to a POSITA; correct?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: The '127 patent does not explicitly dictate the location of the LEDs. Those are choices that a POSITA would make as part of an engineering analysis.

BY MR. STEPHENS:

Q. And is another choice that the POSITA would make as part of the engineering analysis the relative location of the LEDs with respect to the temperature sensor?

A. The relative location of the LEDs and the temperature sensor and the thermal mass, those are all important choices to make, along with dozens of other choices.

Q. And, again, the types of choices that the specification of the '127 patent leaves to a POSITA?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: There are choices that a designer may make that are not specifically articulated in the '127 patent.

BY MR. STEPHENS:

Q. And those choices that are not specifically articulated in the '127 patent, in your view, are left to the skill and discretion of a POSITA in implementing a particular design?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: A POSITA would do engineering analysis and testing in order to make choices and develop designs that satisfy the limitations of the '127 patent.

BY MR. STEPHENS:

Q. Just to confirm, a POSITA would be able to apply his knowledge and skill to make -- to perform the required engineering analysis and testing to make suitable choices and designs that would satisfy the limitations of the '127 patent?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: A POSITA could read and understand the '127 patent, go through a rigorous engineering analysis, work flow, make a host of choices, and develop a successful system that met the description in the '127 patent.

BY MR. STEPHENS:

Q. I'd like to turn back again to

Figure 12, if we could.

So I think earlier we established that when the light emitters 710 are activated, they generate heat; correct?

A. Yes.

Q. And some of that heat is conducted through the thermal mass 1220; is that correct?

A. Some of the mass -- some of the heat emitted by the light emitters -- excuse me.

Some of the heat generated by the light emitters flows into the thermal mass by heat conduction.

Q. Is some of the thermal energy that flows from the light emitters to the thermal mass stored for a time in the thermal mass?

A. The way to think about the heat flow is to understand that the temperature distribution in the LED and the thermal mass is likely varying in space and in time. So we typically refer to temperature distributions in four dimensions, XYZ, three dimensions in space, and one dimension in time.

We can also describe the heat transfer also as a vector quantity that varies in three dimensions of space and one dimension of time. The time variation of the temperature is connected to the storage characteristics, but I think it would be imprecise to say that the heat is stored that refers to more of a quasi static process. So the heat doesn't move into the thermal mass and stay there. The heat is continuously moving. And the temperature changes in time.

Q. I see. Thank you for the clarification.

So as heat is transferred from the LEDs 710 to the thermal mass 1220, how does that affect the temperature of the p-n junctions of the LEDs?

A. Well, most of the heating within the LED occurs at or near the p-n junction. So that is where heat is being generated, and heat flows away from that location. It flows away from that location within the LED. The LED may be packaged. So there may be some supporting or surrounding material to the LED, which also might be considered to be part of the light emitter. And the LED or the packaged LED would be connected to the thermal mass. So heat flows away from the p-n junction into the surroundings.

Q. So -- and that would include heat flowing away from the p-n junctions into the thermal mass in the configuration like what's shown in Figure 12?

A. Yeah, so the p-n junction is a region in the LED semiconductor material. So strictly speaking, you might say that the p-n junction is actually the LED because that is where the light is generated, but, in fact, there is semiconductor material that is not the p-n junction but is part of the semiconductor device.

Q. I see, yeah.

As heat transfers from the LEDs to the thermal mass 1220, how would that affect the temperature of the LEDs themselves?

A. So the heat generation and the heat flow, these are transient phenomenon. So at the location of heating, at the p-n junction or near the p-n junction, the temperature will rise as thermal energy is -- as heat is injected into the device, and then heat will flow away from the p-n junction into the surrounding semiconductor material into any packaging that exists and into the thermal mass. And so there's multiple things happening at the -- that may happen in concert. So it's a little bit of a complicated system.

The heat injection, the heat generation serves to locally raise the temperature; but the thermal coupling between the p-n junctions, surrounding semiconductor material, the thermal mass that serves to cool that -- promote heat transfer away from the p-n junction, which reduces its temperature. So the temperature at the p-n junction is actually a complicated function of many factors.

I'll also just take this opportunity to say that these heating and cooling phenomena that are occurring, they may be changing in time, because the surrounding temperature field is also changing and evolving. All right. So we have heterogeneity of the temperature field and space and in time that affects what happens at the p-n junction.

Q. Is it fair to characterize the thermal environment as fairly dynamic?

A. It is fair to characterize the thermal environment as dynamic, yes. And it is, in fact, these complexities with the three-dimensional transient temperature distribution, the dynamic nature of the LED response, and other aspects of the system, this is the work -- this is one of the reasons for the engineering analysis that's required in order to understand all these tradeoffs and to make good choices for the design of the system. So these things are not trivial to understand or to calculate.

Q. So I think you explained that because of the thermal coupling between the light emitter 710 and the thermal mass 1220, some of the heat that's generated by the light emitters would be transferred from the light emitters themselves to the thermal mass 1220, thereby reducing the temperature to some degree of the light emitter 710;

is that right?

A. So for sure when the light emitters are at a higher temperature than the thermal mass, then heat flows from the light emitters to the thermal mass likely by conduction as -- as a very important heat transfer process. However -- and we may think of that as a cooling process as heat flows from the high temperature light emitters into the thermal mass.

However, that may also be occurring while other things are occurring in the system. So, for example, I could continue to have the LED turned on, and it could continue to, you know, have its temperature increase. Even while there was a cooling heat flow into the thermal mass, the temperature could still be increasing of the LEDs.

And there could be other things going on at the same time. There are other LEDs that may be in the system that are also turning on and off and have their own participation in the heat flows. So it's a very complicated system.

Q. So all other things being equal, would you expect that the temperature of the LEDs would be lower when thermally coupled to a thermal mass 1220 versus a system that lacked a thermal mass?

A. I think in the question that you're asking, I don't know that there's enough information to answer that definitively. But for sure, I can connect the light emitters to a heat sink in order to promote heat flow away from the light emitters.

Q. And here, the thermal mass 1220 functions as a heat sink?

A. I think the thermal mass here provides a resistance to temperature change on a scale for estimating the LED wavelengths.

Q. But -- right. So I understand your view of what the function of the thermal mass is. And so certainly it's designed in order to, you know, achieve the functions that are described in the '127 patent, but there is -- would you agree that there is a cooling effect on the light emitters 710 by virtue of it being thermally coupled to the thermal mass 1220?

A. For sure there is heat flowing from

the LEDs into the thermal mass, and in the absence of other heat being injected into the system, the LED temperatures will be reduced due to heat flow into the thermal mass.

Q. And so as a result of the heat that flows from the light emitters to the thermal mass, would there be a reduction in the wavelength shift of the LEDs 710 due to temperature increases?

A. I'm not sure that there's enough information in the diagram or in your description of its operation for me to know that.

Q. But you cannot preclude that possibility?

A. Which possibility?

Q. The possibility that the -- there would be a reduction in wavelength shift in the LEDs as a result of its coupling to the thermal mass 1220.

A. I believe that the thermal mass could provide a cooling function in addition to its function as a thermal mass, and if that resulted in the LED temperature being reduced, that that LED temperature reduction could then result in a reduction in the wavelength shift.

Q. One moment. I'd like to turn to your declaration.

THE WITNESS: Could we please take a quick break?

MR. STEPHENS: Yeah, this is a good time. Should we take five or ten?

THE WITNESS: Five, please.

MR. STEPHENS: Five? Okay. Let's come back in five minutes.

THE WITNESS: Thank you.

MR. STEPHENS: Thank you.

(Recess from the record.)

MR. STEPHENS: Back on the record.

BY MR. STEPHENS:

Q. Dr. King, did you discuss the substance of your testimony with counsel over the break?

A. No.

Q. I'd like to refer to paragraph 36 of your declaration.

A. Okay.

Q. So take a moment to review 36, and let me know when you complete it.

(Document review.)

THE WITNESS: Okay.

BY MR. STEPHENS:

Q. So you explained that error caused by temperature-induced wavelength shift has been a known problem in the art for many years; correct?

A. Yes.

Q. And solutions have been proposed and attempted -- the proposed solutions in the prior art generally fall into four broad categories.

I just wanted to clarify, is that a typo? Should it refer to five broad categories?

A. There are five categories listed in the paragraph, yeah.

Q. So the second category you refer to "reducing wavelength shift by passively cooling the LEDs to reduce variations in junction temperature"; correct?

A. Yes.

Q. And then the fifth category being "compensating for wavelength shift by using one or more temperature sensors to estimate LED junction temperatures and operating wavelengths"?

A. Yes.

Q. And then going down to paragraph 38, you indicate that "A POSITA would have understood that reducing wavelength shift by heating or cooling the LEDs is fundamentally different than either wavelength-shift-compensation method."

Do you see that?

A. Yes.

Q. Can you explain that difference?

What's the difference -- in other words, what's the difference between a temperature compensation method and a method that involves either actively or passively heating or cooling the LEDs?

A. So the key difference between a passive method and a temperature compensating method would be do I have a feedback control mechanism in the system. So passive technique would -- actually, let me strike the word "passive" here.

So the heating and cooling could be active or passive, but the heating or cooling focuses on actually changing the temperature of the LEDs in order to achieve a shift of the wavelength.

A wavelength-shift compensation relies on inferring or measuring the LED wavelength and then making some type of calculation that would -- that would account for that shift in the system operation.

Q. So in a compensation method, there might be a program or some method for correlating temperature of an LED with its wavelength or wavelength shift?

A. There might be a circuit or some software intelligence or some other mechanism that is cognizant of the wavelength and then compensates for it.

Q. But it's not your -- is it your -- strike that.

Is it your opinion that these methods, i.e., between compensation or active or passive heating and cooling must be mutually exclusive?

A. One could have both temperature control heating and cooling of the LED, as well as compensation.

Q. So you might want to reduce the amount of wavelength shift through heating or cooling, as well as compensation to account for any residual wavelength shift that's not addressed by the heating or cooling methods?

A. I could imagine a strategy that used both of those, yes.

Q. And, in fact, as we just reviewed in Figure 12 of the '127 patent, there could be both a reduction in wavelength shift due to the transfer of thermal energy from the LEDs to the thermal mass, as well as a compensation method that's employed through measuring the bulk temperature; is that correct?

A. Well, the purpose of the '127 patent is a wavelength compensation method. And the role of the thermal mass is to provide a resistance to temperature change. So if we're asking -- you know, if we're thinking about could we have the temperature compensation method of the '127 patent in concert with other thermal design elements that provided some cooling or heating that changed the temperature of the LEDs and affected the wavelength shift, I could imagine a situation where you had a system that met the limitations of the '127 patent and also had some additional heating or cooling of the LEDs that affected the wavelength shift.

Q. We've been focusing, I think, throughout our discussion today on LEDs, but the '127 patent is not limited to just LEDs.

Is that your understanding?

A. I believe it says light sources, yeah.

Q. Are there other types of light-emitting sources for which a temperature compensation method might be useful besides LEDs?

A. I could imagine a temperature compensation method being used for incandescent light bulbs. I could imagine the compensation method being used for a laser light source. So, yes, there could be others.

Q. Is that because an incandescent light bulb or a laser are -- would also -- the wavelength of their emitted light would also be dependent on temperature?

A. For an incandescent light bulb, the wavelength could be dependent on temperature. For a laser, I think it depends -- I believe it depends on the type of laser, how much the wavelength would shift, if at all, but there could also be other reasons for doing temperature compensation other than wavelength shift.

Q. What would some of those reasons be?

A. You'd like to control the power that's being dissipated by the device, for example, in order to provide consistent illumination.

Q. I see.

Is it your understanding that the '127 patent describes additional embodiments in which -- that employ an active cooling method to reduce the amount of wavelength shift?

A. I do not believe that that is described in the claims.

Q. So I'll refer to Column 10 and the paragraph that begins at line 49.

A. Yes, Peltier cooling.

Q. Can you help explain what the patent is referring to here?

(Document review.)

THE WITNESS: So in this paragraph, starting at paragraph -- at line 49, there's actually several concepts that are introduced. The first concept is that the light emitter junction voltage would be measured in order to determine the operating wavelength. So that's an electronic measurement of the -- of the light-emitting device that would allow us to determine the operating wavelength.

The paragraph that -- then goes on to describe that the temperature of the light emitter is controlled by one or more Peltier cells. So a Peltier cell is a thermoelectric device typically introduced to offer local cooling, but, in fact, it could also be used to offer local heating. But it's a -- would be a way of controlling the temperature or at least modifying the temperature of the light-emitting device.

Then the paragraph goes on to talk about other ways to determine the operating wavelength, including the use of optical sensors.

BY MR. STEPHENS:

Q. So the '127 patent contemplates that you could both perform temperature compensation through, for example, measuring the bulk temperature of a thermal mass and also control the temperature of the LEDs through one or more Peltier cells; is that correct?

A. The '127 patent does introduce the concept of having Peltier cells to provide cooling or perhaps heating, which would then modify the operating wavelength of the light emitters.

Q. Would a POSITA know how to use the Peltier cells along with temperature compensation based on bulk temperature?

A. Well, the introduction of the Peltier cells, the design choices that you would make, the size, shape, location of the cells, how they were to operate, that would be part of an overall engineering analysis and testing that one would do in designing a system.

Q. And that would be designing and testing, applying the POSITA skill and knowledge?

A. The POSITA would, you know, read and understand the '127 patent, including the paragraph that's on the screen. And along with their knowledge and experience and additional engineering tasks known to them, they could then design a system, yes.

Q. I'd like to turn to paragraph 42 of your declaration. And this is -- so paragraph 42 begins a discussion of the Cheung reference; correct?

A. Correct.

Q. And you understand that Cheung was cited by the examiner during prosecution of the '127 patent?

A. Yes.

Q. And then if we could go forward to page 25. Yeah.

And so you've reproduced in paragraph 42 on page 25 of your declaration Figure 11 from Cheung, and it looks like you've enlarged and colored and annotated a portion of that figure that depicts a pair of LEDs and a temperature sensor.

Do you see that?

A. Yeah, that's right.

Q. Okay. Do you understand Cheung to be performing a temperature compensation method for accounting for wavelength shift in LEDs?

A. Yes, so the purpose of Cheung is to perform temperature compensation and to enable the device to operate in different environments of different temperatures. So the temperature sensor measures the ambient or the environment temperature. So the purpose is to be able to take this device into different environments that might have different temperatures to compensate for the environment temperature and to be able to make accurate measurements that are insensitive to the environmental conditions.

Q. And Cheung, as you just mentioned, refers to a temperature sensor 50 that indicates a change in the ambient temperature; is that right?

A. Temperature sensor measures the temperature of the ambient surrounding temperature, the environment nearby.

Q. And can you be more specific, when you refer to the environment, what is being detected by the temperature sensor? What would impact the reading of the temperature sensor in Cheung's device?

A. Yeah, so you might take the device and take it outside on a cold day because you have some -- you have a patient you'd like to monitor that's outside in an emergency medicine situation, for example. So you could go outside and be cold -- much colder than it would be inside and -- but the cold weather would cause the whole system to be cold and might result in wavelength shift that would produce an inaccurate reading.

So the purpose of the temperature sensor is to measure the temperature of the nearby environment -- the surrounding air environment and then to use that to compensate for the temperature-induced wavelength shift.

Alternatively, I could take it into a hot location, maybe it's a summer day, you're out in the sun, the system heats up because of the sun illuminating on the system, and that would result in a wavelength shift of the LED. The temperature compensation would measure the temperature of the nearby environment, and then use that to compensate for the temperature shift -- the wavelength shift of the LEDs, enabling inaccurate measurements.

Q. So in order to detect the temperature of the ambient environment, would you expect that a POSITA could have positioned the temperature sensor at a significant distance from the LEDs?

A. So my read of Cheung is that the environment and the temperature sensor and the LEDs are all at the same temperature, which is the ambient temperature. So following that assumption, the operation of the system would be insensitive to the location of the sensor.

Q. Because the ambient temperature is dictated not by the temperature or the heat generated by the LEDs but is a function of the environment independent of the LEDs?

A. And the assumption that the LEDs and the temperature sensor and the environment, by assuming that all those things are at the same temperature, that implies or requires that any self-heating of the LEDs is negligibly small.

Q. Would you expect the -- strike that.

Would you expect the self-heating of the LEDs to be negligibly small compared to changes in the environmental temperature in a practical device?

A. Well, this invention assumes that the temperature sensor and the LEDs and the environment are all at the same temperature.

Q. And so I gather you've come to that understanding because Cheung characterizes its sensor as providing an accurate determination of the wavelength of the light emitted by the LEDs; is that right?

A. Well, Cheung describes temperature compensation of the LED wavelength shift that uses the ambient temperature as part of the temperature compensation.

Q. So in paragraph 43 towards the bottom of page 26 of the declaration, you indicate that "A POSITA also would have also understood that temperature-change resistance in the system is negligibly small. It's reasonable to assume that some two-LED sensor configurations have those characteristics where the two LEDs are located closely to each other and to the temperature sensor [sic]."

A. Yes.

Q. I want to understand what you are specifically referring to in the system as having a negligibly small temperature-change resistance.

A. Hmm. Well, because the temperature sensor and the LEDs and every other element of the system is at the same temperature as the ambient temperature, then -- that occurs when no part of the system, you know, is providing a meaningful temperature-resistance change.

In other words, the LEDs and the temperature sensor and all of the elements of the system are -- have such high degree of thermally coupled that they're all at the same temperature all the time, and that temperature is equal to the ambient temperature.

Q. You just mentioned that the temperature sensor 50 -- or the operation of the Cheung's device is insensitive, I believe was your word, to the positioning of the temperature sensor 50. What -- what thermal pathways in that instance where the temperature sensor 50 is located a far distance from the LEDs have a low resistance to temperature change?

A. Well, I don't believe that Cheung discusses details of the thermal pathways and their thermal resistance, but we can understand from the assumption that everything is at the same temperature, which is equal to the ambient temperature. We can understand that the thermal pathways that are there result in the homogenous temperature equal to the ambient temperature.

Q. So in Figure 11, you can see both -- in this depiction, LED 40, LED 42, and temperature sensor 50 are all disposed on some type of board; correct?

A. Yes.

Q. Do you have an understanding of what that board might be made of?

A. I believe that that's a circuit board that would be made out of conventional circuit board materials, like a polymer laminate FR4 and some metal traces like copper.

Q. What is FR4?

A. It's a polymer composite material that's commonly used for circuit boards.

Q. And what are -- do you have an understanding of the thermal properties of FR4?

A. I do, and I believe I provided those in my declaration.

Q. As a general matter, would you characterize FR4 as a thermal insulator -- more of a thermal insulator or more of a thermal conductor?

A. Certainly more insulating than metal.

Q. Significantly more?

A. Significantly more.

Q. And is there a reason that it's beneficial for -- to have -- to implement a board with high thermal insulative properties?

A. So the design of circuit boards -- actually, the primary consideration for a circuit board is its electronics properties. And FR4 has good electrical insulating properties, low electrical capacitance. FR4 is also inexpensively manufactured and can achieve the dimensions and sizes required for an electronic system. So it has many attractive attributes, but its low conductivity may not be one of them.

Q. Would you characterize an FR4 board like that in Cheung's Figure 11 as having a low resistance to temperature change?

A. Well, because Cheung reports that the temperature sensor and all of the elements of the system are all at the same temperature equal to the ambient temperature, then I know that whatever the thermal properties of the board are, they promote enough heat conduction to -- and other heat transfer processes to enable the ambient-temperature measurement to satisfactorily provide for LED wavelength-shift compensation.

Q. But as shown in Figure 11, would you expect that the equalization, for lack of a better term, between the temperature of temperature sensor 50 and the LEDs is primarily due to the proximity of the temperature sensor to the LEDs; or is it the thermal conduction of heat from the LEDs through the board to the temperature sensor?

A. I don't know that there's enough information in the figure to say that definitively. For sure, thermal conduction in the solid materials, thermal conduction in the surrendering air, radiation, and convection probably all play a role in the heat transfer in the system. But the relative thermal resistances for those different processes combine to result in the whole system being a thermal equilibrium with the ambient temperature.

Q. So is it your opinion that the board in Cheung would qualify as a thermal mass that has temperature resistance on a scale relevant to estimating LED wavelengths?

A. The board in Cheung promotes heat transfer between all the elements and the system. And so I do not know that it is providing a temperature-change resistance. It's not obvious from the figure and the description that it does that.

Q. There's just a little dissonance in my mind between I think our earlier description of Cheung's board being made of FR4, a highly thermal-insulated material, versus the understanding that there's -- that the thermal -- that the board here is conducting heat to equalize the temperature between the LEDs and the temperature sensor 50.

Can you help me to reconcile that?

A. Well, I think there's multiple avenues for reconciling those facts. So, first, we don't know from Cheung that the LEDs are generating heat that -- we do know from Cheung that the whole system is a thermal equilibrium. So even if we were to bring our own knowledge of LEDs to say that there was some heat being generated, whatever heat being generated is flowing away. It is -- so that would be the first issue.

The second issue is that a thermal resistance is -- as I mentioned earlier in our discussion, a thermal resistance is really a proportionality constant between a temperature difference and a heat flow.

So Cheung teaches that there's no temperature difference in the system and so we could say that there's no thermal resistance or negligible thermal resistance or perhaps, more appropriately, we would just say that the concept of thermal resistance is not an appropriate concept here because there's not a temperature change and, thus, no resistance to heat flow.

So objects that have low thermal

conductivity can -- can transmit heat just -- and objects with high thermal conductivity can transmit heat. And so the quantity of heat transmitted in the way that the transmitted heat is proportional to the temperature is how we think about the thermal resistance in this system.

Q. Thermal resistance is a component of but not the same as a resistance to temperature change, as described by the board's construction.

Is that your understanding?

A. So thank you for asking that question. So thermal resistance is a rigorous and well understood concept in heat transfer science and engineering, and it's really the proportionality constant between a temperature difference and a heat flow or the relationship between the temperature difference and a heat flow.

The board's definition for thermal mass providing resistance to temperature change, that has things in common with the more rigorous heat transfer definition of "thermal resistance," but it's not the same.

Q. So just to wrap this up on Cheung, Cheung is not specific about the heat transfer mechanisms that allow the -- or the equalization of temperatures amongst the LEDs and the temperature sensor?

A. That's correct.

Q. This discussion in Cheung in your declaration, which, as we mentioned, began at paragraph 42, is kind of Subsection 1 of a section that begins at paragraph 36, in which you captioned, "Prior Art Techniques for Handling Wavelength Shift" --

A. Yes.

Q. -- is that correct?

And so I see that you've reviewed Cheung starting at paragraph 42; Noguchi, paragraph 44; Webster, paragraph 47 --

A. Yeah.

Q. -- and Huiku, paragraph 51; is that right?

A. Yes.

Q. Did you consider any other prior art

references that describe techniques for handling wavelength shift in the analysis in your declaration?

A. I do not recall considering any other prior art.

MR. STEPHENS: It hasn't been quite a full hour since our last break, but I think this might be a good breaking point, if we'd like to take lunch.

MR. CANNON: That's fine.

THE WITNESS: Okay. Thank you.

MR. STEPHENS: Can we reconvene at 1 Central?

THE WITNESS: Yes, that sounds great.

MR. STEPHENS: Okay. We'll see you then.

(Luncheon recess from the record.)

AFTERNOON SESSION

MR. STEPHENS: Let's go back on the record.

DR. WILLIAM P. KING,

having been previously sworn, resumed the stand and testified further as follows:

EXAMINATION (Cont'd.)

BY MR. STEPHENS:

Q. I'd like to turn to the Yamada reference, which is Exhibit 1004. That is the English translation of Yamada.

A. Okay.

Q. And can we turn to Figure 1, which is, I believe, on page 38.

And in Figure 1, there is a component labeled 1, which is referred to as an optical probe 1.

Do you see that in Figure 1?

A. Yes.

Q. And what's your understanding of the function of the optical probe in Yamada?

A. Let me review Yamada briefly here,

please.

(Document review.)

THE WITNESS: Yes, the optical probe
is where a source of light goes into and
perhaps out of the patient for the purpose of
measuring blood flow.

BY MR. STEPHENS:

Q. And in Figure 5, there is a diagram of
the optical probe 1, a cross-sectional view.
Do you see that?

A. Yes, I see that.

Q. And do you understand what 111 and 112
are referring to?

A. I believe those are LEDs.

Q. And then component 12, what is that?

A. So 111 and 112 are both light-emitting
units.

Q. And then -- right. So then
collectively those are referred to as light-emitting
units, I think, 11?

A. Yeah.

Q. And on the opposite side of -- there's a board 15. I believe there's a light detecter 12?

A. Yes, that's correct.

Q. And so in operation, is it your understanding that the LEDs on the top side of the board are what's shown on the right-hand side of the board 15 in Figure 5 would illuminate the area defined by the cavity above the board, the light would reflect to the patient's tissue, penetrate the tissue and scatter and reflect to the light detection unit 12?

A. That's right, yeah.

Q. And so in Figure 1, you can see the optical probe. It's adapted to be attached to the tip of a patient's finger, here the thumb?

A. Yeah.

Q. And what's your understanding as to why the optical probe would be attached to a finger?

A. I think it could be attached to any location on the patient, any of the digits, any finger.

Q. And the device would be capable of obtaining a suitable signal for measuring the oxygen saturation of the patient?

A. That's right, yeah. And I think you can attach it to any of the fingers or other parts of the body.

Q. In paragraph 40 --

A. Of Yamada?

Q. Of Yamada, that's right. The first sentence states, "The present invention is able to provide an optical probe that is easy to reduce in size."

Do you see that?

A. Yes.

Q. And why might a -- why might the inventors here be interested in reducing the size of the optical probe?

A. Oh, the inventors could be interested in reducing the size of the optical probe for really a variety of reasons. But, you know, what springs to mind just first from the drawings is that by having a miniature element, I can have a component that is approximately the size and shape of the finger to which it's attached, making it easier to, you know, operate the device and avoid any inaccuracies from having, you know, a large device or system connect to, you know, a small portion of the human body.

Q. And you understand that in the combinations that have been presented in the petition, that Apple proposes to apply a thermal core in the board 15 of Yamada's optical probe?

A. Yes, I understand that Apple has proposed that combination.

Q. According to the teachings of Chadwick?

A. Yes, I understand.

Q. In that combination -- that is, Yamada, as modified by Chadwick, thermal core in the board 15 -- would a POSITA understand that the heat capacity of the thermal core would be limited by the relatively small size of the board in an optical probe that attached to the user's finger?

A. So if a POSITA was presented with Chadwick and Yamada and then asked to create a combination of the two, I'm not sure why one would be asked to do that -- well, maybe -- could you ask the question a different way, please?

Q. Yes.

I'm interested in whether there's a practical limit on the heat capacity of the thermal core in the combination due to the small size of the optical probe.

A. So if I were to take the Yamada design and insert a large piece of metal or a piece of -- a material to increase its heat capacity, does the heat capacity of the resulting combination, does it depend upon the size of the metal element that has been introduced, the high heat capacity element?

I think the answer is that it would be possible to add elements to Yamada to change its heat capacity, but the resulting heat capacity -- the resulting thermal performance of the optical probe would depend upon more than just the material that was introduced in its heat capacity.

It would also depend upon other elements of the system, the overall design, and the thermal communication between the different elements, and the thermal coupling between the optical probe unit and the environment.

Q. Okay. I don't think you answered my question. I was interested in the heat capacity of the thermal core in the combination.

Would there be a limit to the heat capacity as a result of the relatively small size of the optical probe?

A. So if the size of the optical probe component is fixed and it's desired to minimize the size of the optical probe, there would be only so much room inside the optical probe that you could use to fill with various elements, including a thermal core. So the peak capacity of the thermal core would depend upon its size and shape and -- and thermal properties.

Q. So the heat capacity of the thermal core would be limited to -- based on the size of the probe in which it's being applied; right?

A. Yeah, the heat capacity of a component that was introduced would depend upon its size, yeah.

Q. And I think you've explained in your declaration that heat capacity is one of the primary factors that influences the temperature-change resistance of a thermal mass in the '127 patent; is that correct?

I can refer you to your declaration, if you'd like.

A. Can you point to the paragraph that you're referring to?

Q. Paragraph 124.

A. Yes, that's right. So as I wrote in my declaration, "Determining that a mass has appropriate temperature-change resistance to be relevant to estimating LED wavelengths involves analysis of at least the following attributes of mass: thermal conductivity, heat capacity, and mass [sic]."

Q. So as a practical matter, then, there would be a limit to how low the resistance to temperature change would be of the thermal core in the Yamada-Chadwick combinations due to the limited size of the optical probe; correct?

A. The thermal properties of the optical core would depend upon the size, shape, and material selection of the various components in the optical probe. So if we were to constrain the size of the optical probe to a specific -- use specific dimensions or a specific volume, then that would place limits on what we could include within the optical probe, and that would affect its thermal properties.

Q. And one of those effects would be that there would be a limit to how low the temperature-change resistance of the thermal core could be in the combination; correct?

A. The heat capacity of the elements of the optical probe unit would be limited by the choice of materials and the size and shape. And so if we were to limit the overall available space or the dimensions of any one component, then that would place constraints on the heat capacity of that component.

Q. Is it your understanding that the available space in Yamada's optical probe would be -- place a constraint on the heat capacity and, therefore, how low the temperature-change resistance of the thermal core could be in the combination?

A. Sorry, I didn't quite understand that question. Could you please ask it a different way?

Q. Would you understand the relatively small size of Yamada's optical probe 1 as constraining how low the temperature-change resistance of the thermal core in the proposed combination could be?

A. As a practical matter, I think that the optical probe may be much larger than the heat-generating LEDs. And because the optical probe is much larger than the heat sources, any introduction of a heat sink or thermal management solution may or may not be limited by the overall size of the optical probe unit.

Q. There would be -- in any event, though, the thermal core must -- is constrained -- the overall size of the thermal core will be constrained by the available space in the optical probe; correct?

A. The overall size of -- if we were to introduce heat-sinking elements, the maximum size of those heat-sinking elements would have to be less than the available size within the optical probe unit. As a practical matter, the -- at the limit where the heat sink fills the entire volume of the optical probe unit, the thermal performance may actually be insensitive to the size of the heat sink.

So one would need to do further analysis to determine, you know, how much the heat-sinking performance depended upon the size of the heat sink in the scenario that you're proposing where the heat sink is large and filling the available volume of the optical probe.

Q. Can we turn to paragraph 149 of your declaration.

And I'd like to refer just generally from paragraph 149 to 155. So if you'd like to take a moment to review, please do.

A. 149 through what?

Q. 155.

(Document review.)

THE WITNESS: Okay.

BY MR. STEPHENS:

Q. So as I understand it, in paragraphs 150 to 152 -- or I think it actually extends to 153, you've compared the thermal conductivity of aluminum and copper to the thermal conductivity of FR4; is that right?

A. Yes, that's right.

Q. And thermal conductivity is one component, in your view, of -- that a POSITA would assess in understanding an object's temperature-change resistance; is that correct?

A. That is correct, yes.

Q. And I think we established earlier that thermal conductivity is an intrinsic property that's independent of the quantity of the object; is that correct?

A. That's correct.

Q. So your -- the conclusion that you've reached in paragraph 153 with respect to thermal conductivity does not account for the mass of the object; correct?

A. The discussion in this section is known in heat transfer science and engineering as a scaling analysis. And what that allows us to do is to consider the main heat transfer processes and the relative magnitudes of the different heat transfer processes just to help us assess what are the parameters that might be important.

So the discussion here shows the extreme differences in thermal resistance and thermal time constant between an FR4 circuit board and replacing the FR4 with a block of copper or aluminum.

Q. Would you expect an FR4 circuit board to function well as a thermal mass in the '127 patent?

A. It could. So the thermal mass limitation is satisfied if the component resists temperature change on a scale relevant to estimating LED wavelengths. So whether a device or a system meets that limitation depends upon the thermal properties and -- but also the geometry and design and also how it's connected to the rest of the system, the thermal coupling, the thermal environment, other issues that I've mentioned in the declaration and in our discussion today.

So taking the thermal conductivity by itself can teach us some things and help us to understand the physics, but meeting the limitation for thermal mass requires more than that.

Q. And, similarly, in paragraph 154, you refer to -- well, it looks like you do another scaling analysis with respect to thermal diffusivity?

A. Yes, I do a scaling analysis about thermal diffusivity and how it relates to the thermal time circuit board.

Q. Is thermal diffusivity also an intrinsic property of a material?

A. Yes, thermal diffusivity is a function of thermal conductivity, heat capacity, and density, and is it is an intrinsic property.

Q. So you could not determine an object's temperature-change resistance solely based on thermal diffusivity and thermal conductivity; is that correct?

A. I may be able to determine the temperature-change resistance based on conductivity and diffusivity if I also had information about the geometry and the thermal coupling of the object to its environment.

Q. And the mass?

A. I would need the mass, also, yes.

Q. Would you need the distance between the temperature sensor and the LEDs?

A. I may.

Q. So the scaling analysis -- analyses that you provided in paragraphs 149 through 154 -- strike that question.

I would like to just go back to Yamada, and look at Figure 5 again.

Again, in Figure 5, we see the board 15; correct?

A. Yes.

Q. And in the proposed combination with Chadwick, the board 15 would be modified so as to include a thermal core; correct?

A. Chadwick would modify the board to introduce a metal element.

Q. Which we've referred to in the petition as a thermal core; correct?

A. I believe you refer to it as a thermal core.

Q. And would a POSITA understand that there's a cost to increasing the size of the board 15 in the optical probe too much?

A. The size of the board 15 would affect the cost of the board, and it would affect the cost of the overall system because the board needs to interface with the rest of the system. The size of the optical probe assembly would also affect the cost of the size of the -- the cost of the optical probe assembly.

It's not clear that bigger always means more expensive for those items. In some cases, smaller could also mean more expensive. So there's extensive engineering tradeoffs in the design and manufacturing and so on that would --

that would govern the cost. So it's not as simple as bigger is more expensive.

Q. Thank you for that.

And I was actually referring to cost in a broader sense, not just monetary cost, but also the cost to the performance or other objectives of the inventors in implementing the probe.

Would there be costs associated with increasing the size of the board 15 substantially?

A. Well, so I could imagine both costs and benefits of changing the size. So perhaps there is some practical size limit beyond which the device stops to function well. If it gets too big, well, it's just attached to a single finger, for example.

But I could also imagine a scenario where one or more of the components would get larger, and that might improve some aspect of the performance of the optical probe. So I think it's -- it's probably difficult to make, you know, generalizations about how the size relates to the costs and benefits of -- of the device performance.

Q. A POSITA would recognize there would

be design tradeoffs?

A. There would be design tradeoffs that a POSITA would recognize, yes.

Q. I'd like to turn back to paragraph 124 of the declaration.

And in this paragraph, it's on -- it's about two thirds of the way down on page 85. The sentence beginning, "In addition, even factors outside of the design of the mass itself, such as the relative locations of the thermistor and LEDs on the board, may affect whether the mass functions as a 'thermal mass' having the appropriate temperature-change resistance."

Do you see that?

A. Yes, I do.

Q. And so here, I think you're referring -- you're making the point that there are kind of -- there are factors external to the mass that can impact the thermal function of the mass and thereby impact whether it qualifies as a thermal mass in the '127 patent?

A. The thermal function of the mass

depends upon a host of parameters that are outside the boundaries of the mass itself, including the location of the LEDs, how they operate, the location of the temperature sensor, the size of the temperature sensor, the thermal coupling between the thermal mass and the environment to the rest of the system, and many other factors.

Q. Okay. With that in mind, can we turn to Figures 15 to 16 of the '127 patent.

Oh, I'm sorry, this is Yamada. So turning to Exhibit 1001, the '127 patent. There we go.

Is it your understanding that Figure 15 shows a first view of a substrate 1200 from one side and Figure 16 shows the opposite side of the substrate 1200?

A. Yes.

Q. And on the first side, shown by Figure 15, there are a plurality of LEDs 801 --

A. Yes.

Q. -- mounted on the substrate?

A. Yes.

Q. Okay. And opposite -- on the opposite side, as shown in Figure 16, component 1540 is a thermistor; correct?

A. Yes.

Q. And in this configuration, is it your understanding that the substrate includes a thermal mass to perform the functions described in the '127 patent?

A. The thermal mass is not viewable on this image, but it's my understanding that there's a thermal mass, yes.

Q. Would a POSITA understand that the temperature sensor 1540 is positioned relative to the LEDs 801, such that the thermal mass would normalize and stabilize the bulk temperature?

A. The thermal function of the thermal mass is not apparent from this figure. The position of the thermistor on the opposite side from the LEDs is consistent with the description in the '127 patent that there is a thermal mass that normalizes and stabilizes the temperature and resists temperature change on a scale relevant for estimating LED wavelengths. So the thermistor position is consistent with my understanding of the '127 patent.

Q. In the context of the description of the '127 patent as a whole, is it your understanding that the substrate 1200 here includes a thermal mass that would, for example, have a temperature-change resistance on a scale relevant to estimating LED wavelengths?

A. So my understanding is that limitation -- or at least some of the claims cite the -- that the thermal mass is disposed within the substrate 1200. But, otherwise, the drawing on the screen is consistent with my understanding of the '127 patent and how it operates.

Q. Fair enough. Sure.

So I'd just like to consider a hypothetical. If we moved the thermistor 1540 from its present location, as shown in Figure 16, to be adjacent to one of the LEDs 801 on the first side of the substrate, such that the thermistor 1540 tracks the temperature of one of the LEDs 801, would the structures in the substrate 1200 still qualify as a thermal mass?

A. So the claims don't require that -- any particular location for -- for the temperature sensor. So it's possible that there could be different configurations of the temperature sensor relative to the plurality of LEDs that would meet the limitations of the '127 patent.

The thermal mass is defined based on its thermal function in terms of resisting temperature change on a scale relevant to estimating LED wavelengths. And so I could imagine many possible configurations of materials and geometries that would result in thermal masses that met the limitations of the claims of the '127 patent.

Now, a thermal mass that meets the thermal mass definition and satisfies the '127 claim requirements, that works for one location of the thermistor, may or may not function as a thermal mass if I were to move the thermistor to a different location.

It may be that if I desired to move

the thermistor to a different location, that I would need to redesign the thermal mass in order to achieve the limitations of the claims and the definition of "thermal mass." But it's also possible that a thermal mass could satisfy the definition of "thermal mass" in the restrictions in the claims for multiple different locations of the thermistor.

So in order to make those determinations and to design those thermal masses, one would need to do engineering work and testing to make those determinations.

Q. Could we turn to Figure 14.

As we discussed earlier, the '127 patent identifies inner layers 1402 through 1405 as a thermal mass?

A. Yes.

Q. And yet, there is no depiction of the relative location of the temperature sensor to the LEDs.

So are you saying that -- is it your view that in Figure 14, these structures may not be a thermal mass if you place the thermistor in the wrong location?

A. Whether the designed system meets the "thermal mass" definition to resist temperature change on a scale relevant for estimating LED wavelengths, that depends on the location of the LEDs and their operating conditions. It depends on the location of the temperature sensor. It depends on the thermal coupling between the elements of the system, the thermal environment, and other factors.

Q. So a POSITA couldn't be sure by looking at Figure 14 alone whether those layers are, in fact, a thermal mass without additional information?

A. Figure 14 alone is not sufficient to determine whether the design meets the definition of "thermal mass" in the claim limitations.

Q. Can we turn to paragraph 88 of your declaration.

So in paragraph 88, you offer your opinion on the last sentence shown here that "the 'bulk temperature' limitations should be construed to mean 'a temperature measurement of the thermal mass that represents (but is not necessarily the same as) LED temperatures'"; correct?

A. Correct.

Q. Is there any disclosure that you are aware of in the '127 patent that quantifies how representative the bulk temperature must be either of the thermal mass or the LEDs?

A. I'm not aware of a location in the '127 patent that quantifies how representative the temperature measurement must be. However, we can understand the '127 patent to teach us that the -- that the measured temperature must be representative in a way that enables the temperature compensation and estimation of the LED wavelength shift.

Q. And does the '127 patent describe how sensitive that temperature must be in order to perform wavelength-shift compensation within a specific tolerance level?

A. I believe that the '127 patent, and specifically the claims of the '127 patent, are satisfied regardless of the magnitude of the temperature compensation.

Q. So is it my understanding, then, that any bulk temperature reading that allows you to compensate to any degree the wavelength shift would satisfy the claims of the '127 patent?

A. Well, the temperature measurement must be representative of the LED temperatures. The '127 patent -- the invention has more than just the temperature sensor. It also has an electronic circuit, and it has software that interprets the electronic signal. So all of those things work together. And so having a more or less accurate temperature measurement may or may not affect the overall temperature compensation because actually you have a system of things that are working together to provide the temperature compensation.

Q. So it's possible that there may be other inputs available besides just the bulk temperature that could aid in more precisely compensating for a temperature-induced wavelength shift?

A. I wouldn't say other inputs, although

I do believe the claims recite the use of current, as well as temperature.

Q. So, for example, you might use dry currents and the bulk temperature together to perform the temperature compensation?

A. I believe the '127 patent reports the use of currents and temperature measurement, yeah.

Q. In a device like those described in the '127 patent, would a POSITA understand that the bulk temperature may correspond more closely to the temperature of some LEDs than others?

A. Well, the physical temperature at the location of the temperature sensor may be closer to or farther away from the actual temperatures of the different LEDs. However, the '127 patent reports a system that can estimate the plurality of temperatures.

So the accuracy or quality of that estimation may or may not depend upon the difference between the temperatures -- the temperature of the temperature sensor and the temperature of the LEDs. Because there's other things going on with the current measurement. There's also software, potentially calibrations, and so on that would allow for the estimation of the LED wavelength shift.

Q. But because of those variations that you mentioned, distances between different LEDs and the thermistor, different thermal pathways between the LEDs and the thermistor, would a POSITA expect that the thermistor would produce a temperature signal that is more representative of some LEDs than others?

A. I think within the context of the '127 patent, I would expect to be able to design a system such that the measurement of the sensor temperature enabled a wavelength-shift compensation for all of the LEDs.

Q. Would a POSITA reviewing the '127 patent know how to configure the LEDs, the thermal mass, and the temperature sensor to obtain a bulk temperature that's representative of the temperature of the LEDs?

MR. CANNON: Objection, beyond the scope and relevance.

THE WITNESS: A POSITA would be able to -- if the POSITA were to read and understand the '127 patent, they would be able to combine that with their experience and knowledge in order to perform the engineering work required to design the thermal mass and the location of the temperature sensor and the software and the electronics that all enable the '127 patent.

BY MR. STEPHENS:

Q. And a POSITA would know how representative the bulk temperature must be may depend on other factors, such as whether you are also considering the dry current of the LEDs to aid in the temperature compensation?

A. Yes, so when I use the word represents here -- "represent" here in my declaration, the meaning is connected to the operation of the system, where you have the temperature measurement and also current measurement and any calibrations and software and the electronic circuit and so on to ultimately provide the wavelength shift.

And when I hear your question, I hear the word "represents" carries some meaning associated with the accuracy with which the temperature sensor is reporting the exact temperature of the LEDs.

And I think that the operation of the system is not dependent upon how closely the temperature sensor tracks the temperature of the LEDs. And so it's possible that the temperature sensor might track the temperature of some of the LEDs closer than the others and yet still be completely representative of all of the LED temperatures, you know, when operated in a system described by the '127 patent.

Q. What is your understanding of the term "bulk" in "bulk temperature"?

A. So I described this in my declaration. The phrase "bulk temperature" is actually used in heat transfer science and engineering, but it's used in a way that's much different than described in the '127 patent.

Typically, bulk temperature refers to

a temperature far away from a heat source or far away from an interface, and I describe that in my declaration. Here, in the context of the '127 patent, that's obviously not the case. And so I interpret the term "bulk temperature" in terms of just what's inside the '127 patent specification.

Q. I think you mentioned that conventionally in the literature, the term "bulk temperature" can be used to refer to a temperature that's far away from a heat source.

How is that different from what's disclosed in the '127 patent?

A. Let's find the location in my declaration that refers to that.

Mr. Stephens, please let me know if you find it. "Bulk temperature" appears 262 times in my document.

Q. Yeah.

Paragraph 100, I'm not sure if that might be what you're referring to.

A. Yes, thank you.

Q. So I -- just going back to my

question, I'd like to understand how "bulk temperature," as used -- in your view, as used in the '127 patent, is different from its meaning in other context a POSITA applied?

A. So the phrase "bulk temperature" is most frequently used in convection heat transfer, where I have a flowing fluid and I have a heat transfer at the interface between that fluid and another fluid or an object.

So the bulk temperature is the temperature far away from that interface and is most -- this is most frequently referred to in transient heat transfer where the things near the interface are changing, but it could also be for steady safety transfer where things at the interface or near the interface are different than they are far away.

And so it could be useful to define, quote-unquote, bulk temperature far away from the interface as one of the important temperatures in the system, understanding that the temperatures in the vicinity of the interface are changing, are different than the bulk.

So this is most frequently used in convection heat transfer, but it can also be used in conduction heat transfer, but in the same meaning, that it's the temperature far away from the interface or far away from a key heat transfer process that's occurring. So it's a way of accounting for a heat transfer -- excuse me, a temperature far away from something important that's happening.

Go ahead.

Q. In those context, why might an engineer be interested in measuring a bulk temperature far away from the interface?

A. Understanding the temperature far away from the interface can be helpful or even essential in quantifying the heat transfer at an interface. So this is most frequently used in transient problems. Let's say, for example, I have a pot of hot water, and I drop something cold into the pot of hot water. In order to -- a solid object that's cold.

So in order to calculate the heat transfer between the solid object and the pot of hot water, I need to know the temperature of the water far away from the interface between the solid and the liquid. So that's a calculation that requires the, quote-unquote, bulk temperature.

Q. Is there typically a thermal coupling between the location where the thermal -- the bulk temperature is taken and the interface?

A. Yeah, typically, the bulk temperature is helpful in calculating the heat transfer elsewhere in the system, especially at the interface, yes.

Q. Are you aware of any literature that describes bulk temperature in those types of context?

A. I believe in my declaration, I cite a textbook that refers to the bulk temperature.

Q. In the context of convection heat transfer?

A. Yes.

Q. Would a POSITA understand that the

bulk temperature in -- taken in the '127 patent is taken at a distance from the interface between the LEDs and the thermal mass?

A. So a POSITA reading the '127 patent would see the mention of bulk temperature and would understand that the bulk temperature referred to in the '127 patent is much different than the concept of how bulk temperature is used in textbooks and in heat transfer engineering literature.

And so because they would understand the named -- the cited bulk temperature in the patent to be different, they would look more deeply to try to understand, Well, if this is isn't the bulk temperature that I know from literature, what do we actually mean by bulk temperature, and then interpret what bulk temperature means from the context of the '127 patent.

Q. I understand that's what your declaration states.

A. Okay.

Q. I -- you've just explained to me that conventionally bulk temperature is used to measure -- to characterize a thermal process at a distance from a heat source at an interface, and I'm trying to understand how that is different from what's proposed in the '127 patent.

A. So I believe what you just said was -- I believe you were trying to restate my explanation of bulk temperature, and I think you maybe -- you said something that was not accurate.

The bulk temperature is not used to track the temperature or to track a process. The process isn't far from the interface. The process is near the interface. But the bulk temperature is the temperature far away that's helpful for understanding what occurs at the interface.

In the '127 patent, the bulk temperature is just the temperature that's measured by the thermistor, which has nothing to do with convection heat transfer.

Q. But you've indicated that bulk temperature could be used in many context, correct, beyond just convection heat transfer?

A. Yes, you could use bulk -- you could

use the concept of bulk temperature, as described in heat transfer textbooks, to refer to conduction heat transfer processes, as well as convection heat transfer processes. And I could imagine also for radiation heat transfer processes, where bulk temperature would allow you to describe a situation where there was a temperature far from a heat transfer process, but that temperature was important for calculating something about the process.

Q. So -- excuse me.

I'd like to understand how does your proposed construction of bulk temperature account for the term "bulk" in the term "bulk temperature"?

A. I am not sure that it does. I think the proposed construction for bulk temperature reads the plain language of the '127 patent; that is, just the bulk temperature is the temperature that's measured at the thermal mass.

Q. So if the specification had used some other term for that temperature besides "bulk," your understanding of the term "bulk temperature" would still be the same?

A. My understanding of the term "bulk temperature" would be the same. In fact, I would have preferred if they used a different phrase or word because then it would have been less confusing.

MR. STEPHENS: All right. You want to take a five-minute break now? Would that be all right?

THE WITNESS: Okay. That's fine.

MR. STEPHENS: Okay.

(Recess from the record.)

MR. STEPHENS: Back on the record.

BY MR. STEPHENS:

Q. Dr. King, did you discuss the substance of your testimony with counsel during the break?

A. No.

Q. And I don't think I asked when we got back from lunch, but I just want to confirm, did you discuss the substance during the lunch break?

A. No discussion.

Q. All right. Let's turn to paragraph 36 of your declaration again.

And here, as we discussed earlier, you've identified five general categories of solutions for correcting for error caused by temperature-induced-wavelength shift; correct?

A. Yes.

Q. And in paragraph 41, you explain that the '127 patent is within the fifth general category, "compensating for wavelength shift by using one or more temperature sensors to estimate LED junction temperatures and operating wavelengths"; correct?

A. Yes. Yes.

Q. So that general notion of compensating for wavelength shift by using one or more temperature sensors to estimate LED junction temperatures and operating wavelengths was known in the prior art; correct?

A. I am not recalling the prior art, but yes, I believe there is prior art on it.

Q. I would just refer to the caption of paragraph 36 in the section, "Prior Art Techniques for Handling Wavelength Shift."

A. Sure, yep.

Q. Yeah, so just to confirm, the concept of the solutions of the fifth category were known in the prior art?

A. I'm not recalling the prior art that reports that.

Q. I think you may be referring to prior art generally, what preceded the '127 patent, but correct me if I've mistaken.

A. I think that's correct.

Q. And then further down in paragraph 41, you state that "a POSITA would have considered using a temperature sensor placed as close as possible to the LED to enable accurate measurements of the ambient temperature..."; is that correct?

A. Yes.

Q. And that would be similar to an approach described in Cheung?

A. Cheung measures ambient temperature and assumes that the LED is at the ambient temperature.

Q. And as I read paragraph 41, it seems

that you're identifying two general approaches that fall within the fifth category compensating for wavelength shift, first being "It would have been intuitive for a POSA to attempt to measure or estimate the LED junction temperature as directly as possible," which I think you indicate could be done with dry current or forward voltage drop.

A. Yes.

Q. And then the second approach being the alternative sentence, "a POSITA would have considered using a temperature sensor placed as close as possible to the LED to enable accurate measurements..."?

A. Yes. Yes.

Q. So based on your understanding of the '127 patent, what's the difference or differences between these prior art approaches and the purported invention of the '127 patent?

A. Among other things, the '127 patent has a thermal mass that allows the temperatures of multiple LEDs to be estimated and the wavelengths of multiple LEDs to be temperature compensated through the use of thermal mass in a single temperature sensor.

Q. So the thermal mass is, in your view, a key distinction between these prior art approaches and the approach described in the '127 patent?

A. The thermal mass and its application for enabling a single temperature sensor to provide for temperature compensation -- wavelength-shift compensation of multiple LEDs.

Q. Now, the prior art approaches, as, for example, illustrated by Cheung, demonstrated that you could use a single temperature sensor to perform -- to compensate for temperature-induced-wavelength shift or multiple LEDs; is that right?

A. I think the key differences with Cheung include that Cheung lacks a thermal mass. And the case of Cheung having multiple LEDs is trivial because all of the LEDs are the same temperature, which is equal to the ambient temperature.

Q. When you signed your declaration, were you aware of any prior art that described the use of a thermal mass in a system that performed temperature -- that performed temperature compensation to estimate the operating wavelengths of a group of LEDs?

A. When I signed my declaration, I was not aware of any prior art that reported a thermal mass and single temperature sensor used to estimate and compensate the wavelengths of multiple LEDs.

Q. So you considered that concept to be not known to a POSITA, not part of the prior art?

A. I considered that concept to be novel and not known in the prior art, yes.

Q. Would any of the opinions in your declaration have changed if you had been aware of such prior art?

A. If I had been aware of such prior art, I may need to reconsider some of the aspects of my declaration.

Q. Such as?

A. As I sit here, I'm not exactly sure which portions that I would need to reconsider, but perhaps some of the arguments around motivation to combine or obviousness. I would have to revisit those and think more clearly about what this new information -- what the implications might be.

Q. Could we go up to paragraph 40 of your declaration.

So in paragraph 40, you refer to a United States Patent Application Publication No. 2005/0279949 A1 to Oldham.

A. Yes.

Q. Do you see that?

And according to your testimony in paragraph 40, you indicate that Oldham "uses a temperature sensor to control active heating and cooling devices (such as heaters and fans) to heat up or cool the LEDs based on the temperature reading of the temperature sensor to attempt to maintain target LED temperatures or operating wavelengths"?

A. Yes.

Q. Did you review Oldham when you prepared this declaration?

A. Yes, I did.

Q. Was there a reason that you did not include Oldham in the table of materials considered in paragraph 3 of your declaration?

A. If Oldham is not in the table of materials, that was my mistake.

Q. But you are familiar with Oldham?

A. Yes, I am.

Q. One moment.

MR. STEPHENS: I don't believe that Oldham is an exhibit of record in this proceeding. Counsel, I don't know if you agree with that or if I've overlooked something.

MR. CANNON: I think you're probably right. I haven't -- I think it's probably not in --

MR. STEPHENS: Okay. I'd like to present Oldham -- can I drop that in the chat window?

THE HOTSEATER: You can do that, and I can index it and have it set up.

MR. STEPHENS: Great.

THE HOTSEATER: Let me get that indexed.

MR. STEPHENS: And if we could identify this as Exhibit 1050, please.

(Exhibit 1050, Oldham Patent Application Publication US 2005/0279949 A1.)

BY MR. STEPHENS:

Q. Does this reference look familiar to you, Dr. King?

A. Yes, it does.

Q. Could we go to Figure 1.

And do you know what is generally shown in this diagram, specifically components 118 and 110 and 111?

A. We'll have to refer to the specification to refresh my memory. I believe 111 is a plurality of LEDs.

Q. I believe that's correct, yes.

And then 118 is a temperature sensor?

A. Yes, of course.

Q. And so is it your understanding from Figure 1, that a -- this LED -- I'm sorry, this temperature sensor, single temperature sensor 118, is sensing a temperature that is here used to control active heating or cooling of the LEDs 110?

A. It's my understanding that 114 is a fan that is cooling the system to affect the LED temperatures and the wavelength shift. And I believe 118 is measuring the temperature, yes.

Q. Can we go to paragraph 41.

And about halfway down, there's a description starting with "According to various embodiments, the temperature of an LED can be monitored and a computing apparatus can adjust the detection data to compensate for the spectral shifts and/or intensity changes of excitation beam emitted from the LED."

A. Yes.

Q. And then the following sentence refers to different wavelengths of LEDs, plural.

So would you agree that this is describing a temperature-compensation approach as opposed to active heating or cooling to reduce the spectral shift in LEDs?

A. Let me take a few minutes to review the specification, please.

(Document review.)

THE WITNESS: Okay. I think I'm ready.

BY MR. STEPHENS:

Q. Great. So I just wanted to confirm. In paragraph 41, is this describing an approach for temperature compensation of temperature-induced -- excuse me, compensating for temperature-induced spectral shift?

A. The word "compensate" is on the screen. So it appears that the temperature of the LED can be monitored, and the wavelength shift of the LEDs is known as a function of temperature. And so the actual wavelength emitted by the LEDs can be calculated from the LED temperature measurement.

I'm not exactly sure the purpose of the compensation or what the software and the circuit is actually doing here. So I don't know -- from just reading it here, I don't know if this is the same compensation or how it might be different than the compensation in the '127 patent. That's not clear to me.

But for sure, the spectral shift is being calculated and the -- you know, the LED temperature -- excuse me, the temperature sensor measurement is informing that calculation.

Q. In paragraph 40 of your declaration, where you described Oldham, was there a reason that you omitted the description of spectral shift compensation?

A. There was no reason, no. The paragraph 40 is part of a description of various strategies for mitigating wavelength shift. And so here with Oldham, I was focused on the presence of the fan for cooling.

Q. Which would be within one of the other general categories of --

A. That's right.

Q. -- error correction?

A. Sure.

Q. Can we turn to paragraph 177 of your declaration.

And the second sentence, you state, "Even if a POSITA would have desired to add some form of wavelength shift compensation to Yamada and Chadwick, the prior art would have motivated the POSITA to use ambient temperature, drive currents, or forward voltage drop to perform such compensation."

And then you go on to reference Cheung and Noguchi as prior art approaches.

A. Yes. Yes.

Q. When you made this statement, had you accounted for Oldham's disclosure at paragraph 41 and surrounding text?

A. I recall reviewing Oldham in the context of the presence of the fan and the cooling and not in the context of the temperature compensation.

Q. Do you recall considering any other prior art besides Yamada, Chadwick, Cheung, or Noguchi when you made this assertion in paragraph 177?

A. I did not consider any other prior

art.

Q. And then the next paragraph, paragraph 178, you indicated that "While some prior art called into question the accuracy of wavelength-shift compensation using a temperature sensor when the LED temperatures differ from each other, nothing in the prior art or in any other evidence before the '127 patent suggested that measuring a bulk temperature of a thermal mass would solve the problem."

And you go on to reference Webster, Noguchi. Had you considered any other prior art besides Yamada, Chadwick, Webster, Noguchi, and Cheung in making this assertion?

A. No.

MR. STEPHENS: All right. I'd like to just enter a few more exhibits into the record. I'll drop them into the chat window.

THE HOTSEATER: What exhibit number do you want?

MR. STEPHENS: Let's assign this one 1051, please.

(Exhibit 1051, IEEE paper by Subramanian Muthu.)

BY MR. STEPHENS:

Q. Can you see that, Dr. King?

A. Yes, I can.

Q. So what we've entered as Exhibit 1051 is an IEEE paper by Subramanian Muthu entitled "Red, Green, and Blue LEDs for White Light Illumination."

A. Yes, I'm looking at it now.

Q. Had you considered this reference when you prepared the opinions in your declaration?

A. No, I did not.

MR. STEPHENS: All right. I'd like to enter another document into the record as Exhibit 1052.

(Exhibit 1052, US Patent publication number 2003/0230765.)

BY MR. STEPHENS:

Q. And on the screen, we're showing what's just been entered as Exhibit 1052, U.S. Patent Publication No. 2003/0230765.

Do you see that, Dr. King?

A. Yes, I do.

Q. Do you recall reviewing this reference when you prepared your declaration?

A. No, I do not.

MR. STEPHENS: I'd like to enter another document into the record as 1053, which is the Man reference, U.S. Patent Publication 2010/0259182.

(Exhibit 1053, US Patent Publication 2010/0259182.)

BY MR. STEPHENS:

Q. Do you see that, Dr. King?

A. Yes, I do.

Q. Had you considered this reference when you prepared the opinions in your declaration?

A. No.

MR. STEPHENS: I'd like to enter one additional exhibit into the record as Exhibit 1054.

(Exhibit 1054, US Patent 7,055,986 to Littleton.)

MR. STEPHENS: And Exhibit 1054 is U.S. Patent 7,055,986 to Littleton.

BY MR. STEPHENS:

Q. Can you see that on the screen, Dr. King?

A. Yes.

Q. Had you considered this reference when you prepared the opinions in your declaration?

A. No.

MR. STEPHENS: Thank you, Dr. King. I have no further questions.

MR. CANNON: Let's take about a ten-minute break, and I need to decide if I've got any questions. Is that okay?

MR. STEPHENS: Sounds good.

(Recess from the record.)

MR. CANNON: Is everyone ready?

MR. STEPHENS: Ready.

EXAMINATION

BY MR. CANNON:

Q. Good afternoon, Dr. King. A few questions for you.

Has anything during this deposition today changed your opinion with respect to the alleged obviousness about the '127 patent?

A. No.

Q. You were shown Exhibit 1050, which is the Oldham reference.

Was the Oldham reference used by -- relied on by Apple in its petition in this case?

A. I believe it was.

Q. Exhibit 1051 for Muthu, and you had testified you had not considered this reference; correct?

A. That's correct.

Q. And was this reference used by Apple in its petition?

A. I don't know.

Q. And Exhibit 1052 for Dry, are you aware of whether Apple used this reference in its petition?

A. I don't know.

Q. And Exhibit 1053, the Man reference, are you aware of whether Apple used this reference in its petition?

A. I don't know.

Q. And Exhibit 1054, the Littleton reference, are you aware of Apple using this reference in the petition?

A. I don't know.

Q. Now, when you -- you reviewed the declaration of Dr. Anthony; correct?

A. Yes, I did.

Q. Were any of the references, Exhibits 1050 through 1054, cited in the prior art combinations that Dr. Anthony asserted against the '127 patent?

A. I don't recall.

MR. CANNON: Okay. I am going to just enter onto the record of the deposition an objection to Exhibits 1050 through 1054. And the objection is that they are not relevant under 402 to the grounds in this IPR and that they are untimely presented new evidence. And so I'd just like to enter those onto the record of the deposition.

And with that, I have no further questions.

MR. STEPHENS: I have no further questions.

(Examination concluded. The time is 4:00 p.m.)

STATE OF NEW YORK)
ss:
COUNTY OF WESTCHESTER)

I, EILEEN MULVENNA, CSR/RMR/CRR, a Certified Court Reporter, Registered Merit Reporter, Certified Realtime Reporter, and Notary Public in and for the State of New York, do hereby certify:

That I reported the taking of the deposition of the witness, DR. WILLIAM P. KING, commencing on the 8th day of August, 2023, at the hour of 10:00 a.m.

That prior to being examined, the witness was duly sworn by me to testify to the truth, the whole truth, and nothing but the truth.

That I thereafter transcribed my said shorthand notes into typewriting and that the typewritten transcript of said deposition is a complete, true and accurate transcription of my said shorthand notes taken down at said time, and that a request has been made to review the transcript.

I further certify that I am not a relative or employee of an attorney or counsel of any of the parties, nor a relative or employee of any attorney or counsel involved in said action, nor a person financially interested in the action.

IN WITNESS WHEREOF, I have hereunto set my signature this 17th day of August, 2023.

Eileen Mulvenna

Eileen Mulvenna, CSR/RMR/CRR

Dr. William P. King, c/o
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Case: Apple, Inc. v. Masimo Corp.
Date of deposition: August 8, 2023
Deponent: Dr. William P. King

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Deposition Date: August 8, 2023

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Page No.	Line No.	Change
63	8	"inter leafed" to "interleaved"
70	17	"thermal" to "thermal mass"
103	7-8	"have such high degree of thermally coupled" to "have such a high degree of thermal coupling"

29 Aug 2023

Signature Date

US 20050279949A1

(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2005/0279949 A1**
Oldham et al. (43) **Pub. Date: Dec. 22, 2005**

(54) TEMPERATURE CONTROL FOR LIGHT-EMITTING DIODE STABILIZATION

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(21) Appl. No.: **10/981,440**

(22) Filed: **Nov. 4, 2004**

Related U.S. Application Data

(63) Continuation-in-part of application No. 10/440,719, filed on May 19, 2003, which is a continuation-in-part of application No. 10/216,620, filed on Aug. 9, 2002, which is a continuation of application No. 09/700,536, filed on Nov. 29, 2001, now Pat. No. 6,818,437.

(30) **Foreign Application Priority Data**

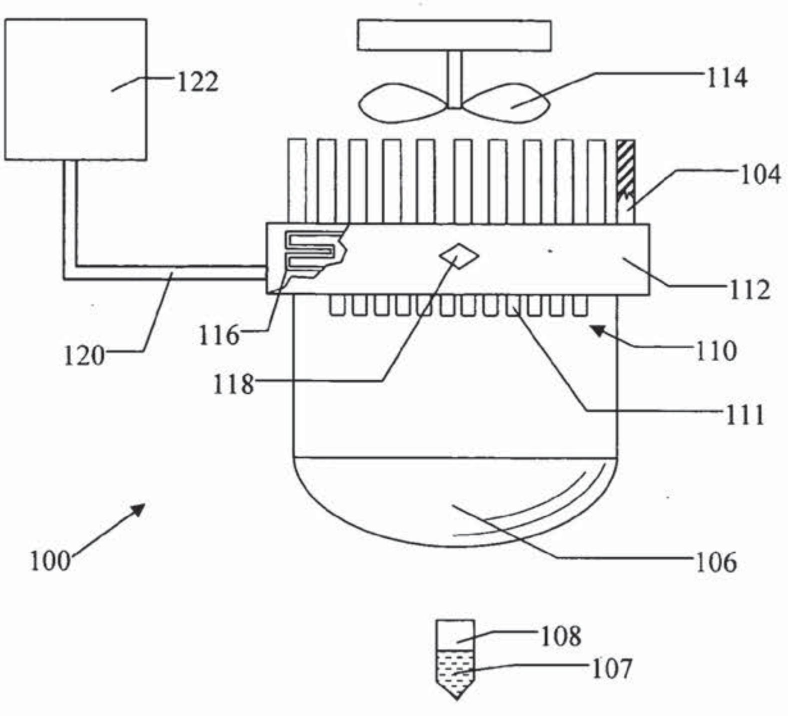
May 17, 1999 (WO) PCT/US99/11088

Publication Classification

(51) **Int. Cl.**^{7} **G01N 21/01**; F21V 9/16
(52) **U.S. Cl.** **250/458.1**; 356/244

(57) ABSTRACT

A system is provided that includes a light-emitting diode (LED); a temperature sensor in thermal contact with the LED and capable of measuring an operating temperature and generating an operating temperature signal; and a temperature regulating system capable of receiving the operating temperature signal and regulating the operating temperature based on the operating temperature signal. A method for stabilizing the temperature of an LED is provided. A method is provided that includes providing a system comprising an LED, a reaction region, and a sample in the reaction region; generating excitation beams with the LED; directing excitation beams to the sample; detecting an optical property of the sample to obtain detection data; measuring the operating temperature of the light emitting diode; and adjusting the detection data of an excitation beam characteristic shift related to the operating temperature, when the LED is operated at the operating temperature to generate the excitation beams.



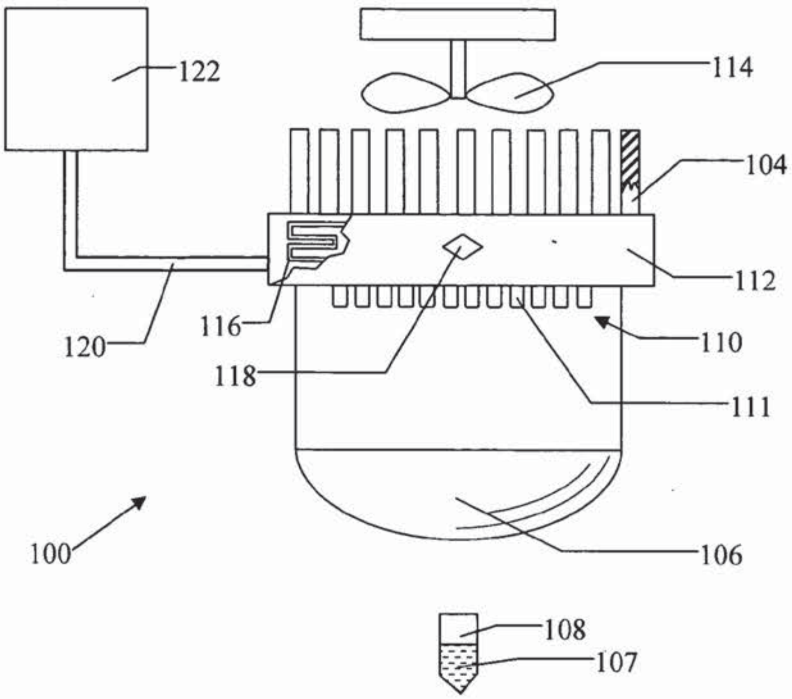

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FIG. 1

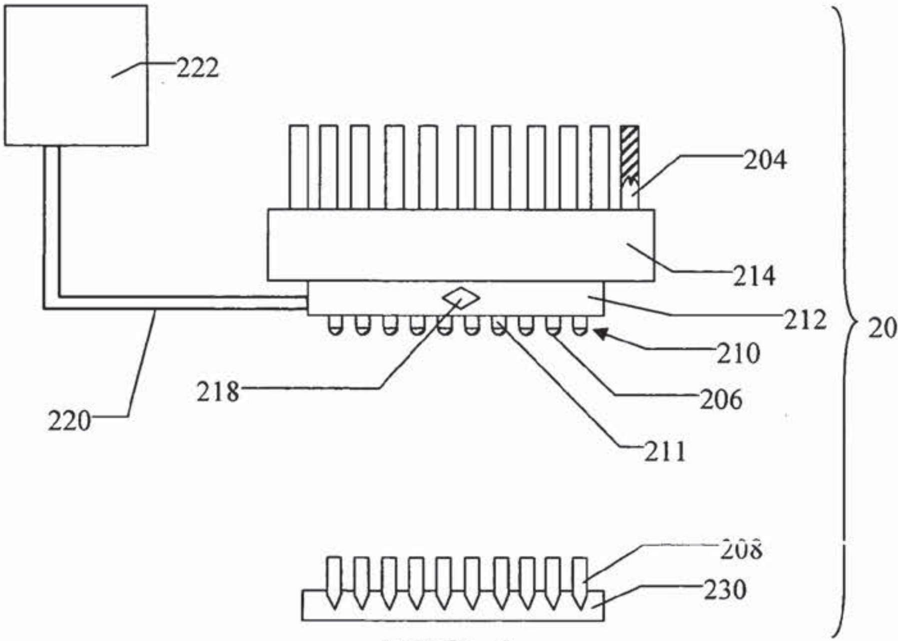
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FIG. 2

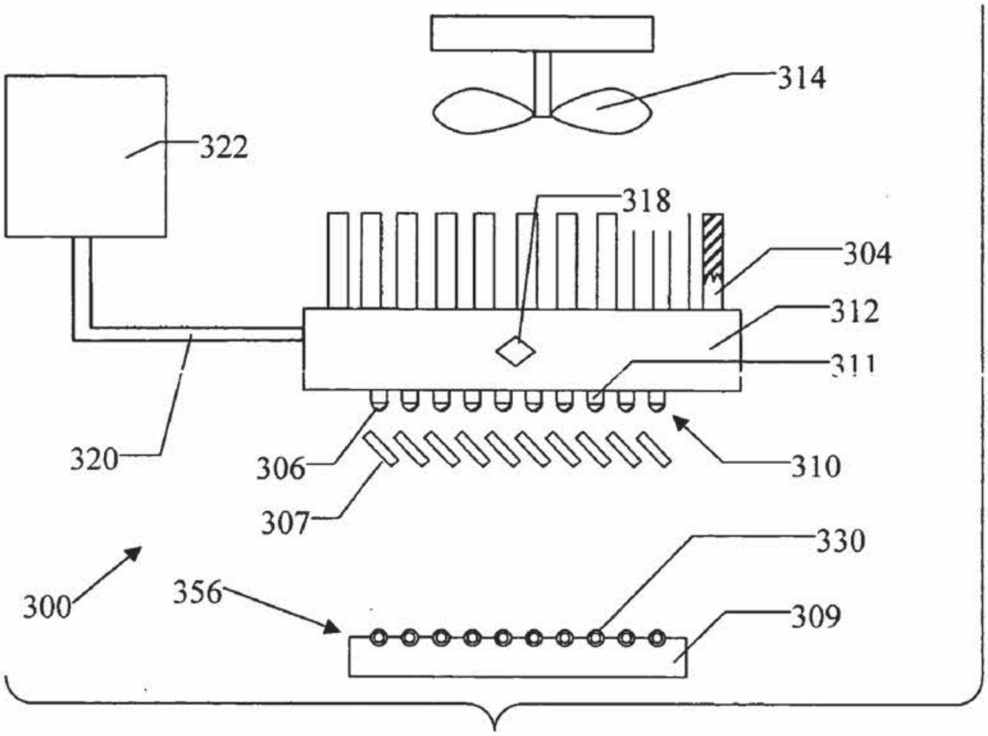
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FIG. 3a

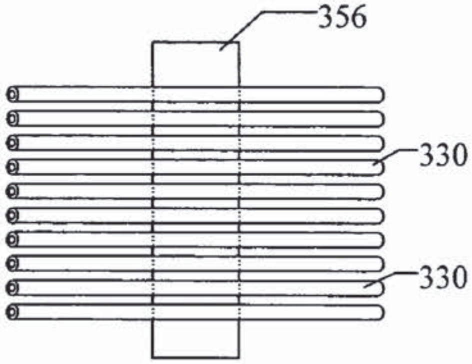
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FIG. 3b

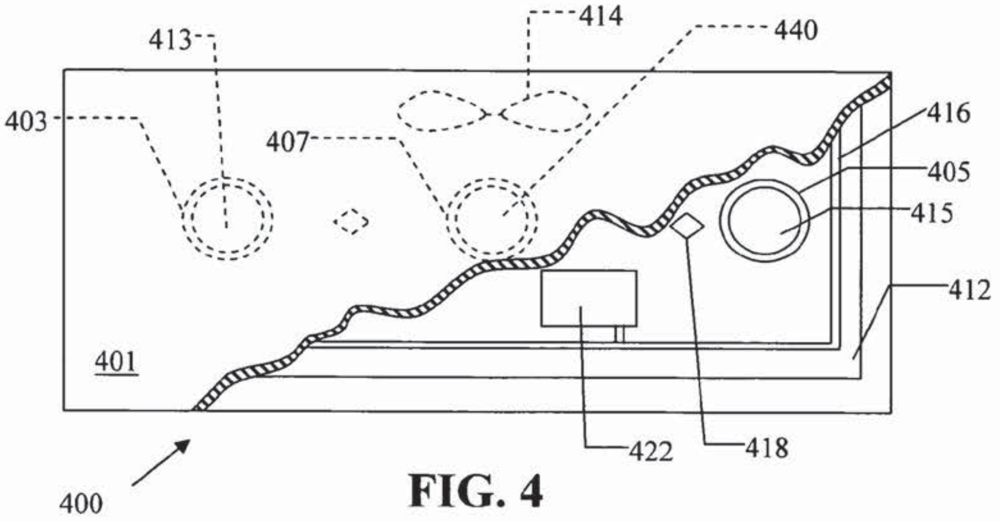
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FIG. 4

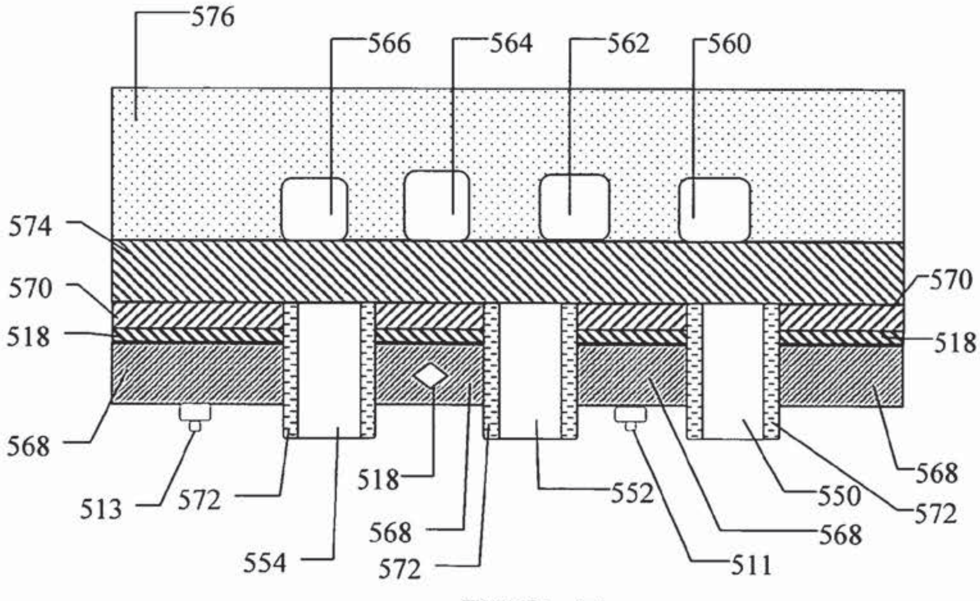
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FIG. 5

TEMPERATURE CONTROL FOR LIGHT-EMITTING DIODE STABILIZATION

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application is a continuation-in-part of co-pending U.S. patent application Ser. No. 10/440,719, filed May 19, 2003, which in turn is a continuation-in-part of co-pending U.S. patent application Ser. No. 10/216,620, filed Aug. 9, 2002, which in turn is a continuation of co-pending U.S. patent application Ser. No. 09/700,536, filed Nov. 29, 2001, which claims priority to PCT/US99/11088, filed May 17, 1999, which published as publication number WO 99/60381 on Nov. 29, 1999, all of which are incorporated herein in their entireties by reference. Cross-reference is made to co-pending U.S. patent application Ser. No. 10/440,920 entitled "Optical Instrument Including Excitation Source" to Boege et al. (Attorney Docket No. 5010-027-01), co-pending U.S. patent application Ser. No. 10/440,852 entitled "Apparatus And Method For Differentiating Multiple Fluorescence Signals By Excitation Wavelength" to King et al. (Attorney Docket No. 5010-047-01), both filed on May 19, 2003, and to U.S. patent application Ser. No. 10/735,339, filed Dec. 12, 2003, all of which are incorporated herein in their entireties by reference.

FIELD

[0002] The present teachings relate to an optical instrument using excitation beams generated by a light-emitting diode.

BACKGROUND

[0003] Light-Emitting Diodes (LEDs) can be used as an excitation source for optical detection, for example, in fluorescent measurement. There is a need for providing an LED excitation beam source that does not exhibit beam intensity changes and/or spectral shift. A device compatible with nucleotide amplification reactions, detecting such reactions, and capable of processing a relatively large number of amplification reactions is desirable.

SUMMARY

[0004] According to various embodiments, a system is provided that includes one or more light-emitting diode (LED), a temperature sensor, and a temperature regulator. The temperature sensor can be in thermal contact with the LED, can be capable of measuring an operating temperature, and can be capable of generating an operating temperature signal. The temperature regulator can be capable of receiving an operating temperature signal of the LED and regulating the operating temperature based on the operating temperature signal. Herein, it is to be understood that by LED what is meant is at least one LED, and that a group or array of LED's can be included in an "LED" as described herein.

[0005] According to various embodiments, a method for illuminating a reaction region with excitation beams is provided. The method can include providing a system that includes an LED and a reaction region. The method can include generating excitation beams with the LED; directing the excitation beams toward the reaction region; measuring an operating temperature of the LED; and regulating the operating temperature by transferring heat away from and/or into the LED, based on the measured operating temperature. The reaction region can include a sample retained therein.

[0006] According to various embodiments, a method for illuminating a reaction region with excitation beams is provided. The method can include providing a system that includes an LED and a reaction region. The method can include generating excitation beams with the LED; directing excitation beams to the sample; detecting an optical property of the sample to obtain detection data; measuring the operating temperature of the light emitting diode; and adjusting the detection data based on the operating temperature. The adjustment can be made, for example, by shifting the detection data. The shifting of the detection data can include, for example, a shift in intensity, spectra, or both.

[0007] Additional features and advantages of various embodiments will be set forth in part in the description that follows, and in part will be apparent from the description, or can be learned by practice of various embodiments. Other advantages of the various embodiments will be realized and attained by means of the elements and combinations exemplified in the application.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Various embodiments of the present teachings are exemplified in the accompanying drawings. The teachings are not limited to the embodiments depicted in the drawings, and include equivalent structures and methods as set forth in the following description and as would be known to those of ordinary skill in the art in view of the present teachings. In the drawings:

[0009] **FIG. 1** is a side view in partial cross-section of a system including a heater providing temperature stabilization for an LED array according to various embodiments;

[0010] **FIG. 2** is a view in partial side cross-section of a system including a thermoelectric device providing temperature stabilization for an LED array according to various embodiments;

[0011] **FIG. 3***a* is a side view in partial side cross-section of a system including a fan and cooling fins providing temperature stabilization for an LED array according to various embodiments;

[0012] **FIG. 3***b* is a top plan view of a capillary sample holder according to various embodiments;

[0013] **FIG. 4** is a top view in partial cross-section of a system including a fan and heating element providing temperature stabilization for an LED according to various embodiments; and

[0014] **FIG. 5** is a side view in a partial cross-section of a system providing a strong thermal conductive path according to various embodiments.

[0015] It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are intended to provide a further explanation of the various embodiments of the present teachings.

DESCRIPTION OF VARIOUS EMBODIMENTS

[0016] According to various embodiments, a system is provided that includes one or more light-emitting diode

(LED), a temperature sensor in thermal contact with the LED, and a temperature regulator. The temperature sensor can be capable of measuring an operating temperature and generating a signal. The signal can include an operating temperature signal. The signal can be a digital signal. The digital signal can be indicative of whether the temperature being sensed is above or below a set point. The temperature sensor can generate a signal without thermal contact with the LED. The temperature sensor does not have to directly generate an operating temperature signal but rather can simply indicate whether a temperature is above or below a set point. The temperature regulator can be capable of receiving the operating temperature signal and regulating the operating temperature based on the operating temperature signal.

[0017] According to various embodiments, the system can include a heat-transfer device and a control unit capable of controlling the heat-transfer device. The heat-transfer device can include a fan capable of forming an air current in thermal contact with the LED. The heat-transfer device can include a cooling fin in thermal contact with the LED. The heat-transfer device can include a heater in thermal contact with the LED. The heat-transfer device can include a thermoelectric device in thermal contact with the LED. The thermoelectric device can be connected to a reversible-DC-power supply. According to various embodiments, the temperature regulator can include a temperature system that can be capable of increasing and/or decreasing the operating temperature of the LED.

[0018] According to various embodiments, the temperature regulator can comprise a system adapted to control excitation of one or more fluorescent dyes. The temperature regulator can be adapted such that it is capable of maintaining the operating temperature within an operating temperature range including a minimum temperature and a maximum temperature separated by, for example, about 15° C., about 5° C., about 1° C., or about 0.5° C. The operating temperature range can also be specified as a nominal temperature and an acceptable deviation value range.

[0019] According to various embodiments, the temperature regulator can be a temperature regulating system that can include a user input device that is capable of being programmed to maintain an operating temperature range including a minimum temperature and a maximum temperature. The system can include a display capable of displaying the operating temperature signal.

[0020] According to various embodiments, the system can include an error signaling device capable of signaling an alarm when the operating temperature is greater than a maximum temperature. The error signaling device can signal an alarm when the operating temperature is less than a minimum temperature.

[0021] According to various embodiments, the system can include a substrate in contact with the LED. The substrate can include, for example, a Printed-Circuit Board (PCB). According to various embodiments, the reaction region can include a sample retained therein.

[0022] The sample can include one or more nucleotide. The reaction region can include reagents necessary to perform a nucleic acid sequence amplification reaction. The sample can include fluorescent dyes, labels, or markers. The system can include a detector capable of detecting an optical property of the reaction region.

[0023] According to various embodiments, the temperature sensor can include a thermister, a thermocouple, a resistance temperature detector (RTD), a bandgap semiconductor temperature sensor, a non-contact temperature sensor, a bandgap semiconductor resistive temperature detector, a platinum resistive temperature detector, a bi-metallic temperature detector, a combination thereof, or the like.

[0024] **FIG. 1** is side cross-sectional view of a system **100**, according to various embodiments, including an LED array **110** that includes a plurality of LEDs **111**. The system can also include a focal lens **106**. The focal lens **106** can focus excitation beams emitted by the LED array **110**. The LED array **110** can be in physical and/or thermal contact with a substrate **112**. The LED array **110** can include one or more rows or patterns of individual LEDs. The substrate **112** can be a PCB. A heating device **116**, for example, a resistive heating element, can be provided in thermal contact with the LED array **110**. The heating device **116** can be included in, on, or in and on the substrate **112**. The system **100** can include a temperature sensor **118** in thermal contact the LED array **110**. The temperature sensor can be centrally located with respect to the LED array **110**. The temperature sensor **118** can be included on the substrate **112**. A temperature regulator or temperature regulating system **122** can be provided that is capable of receiving a signal from the temperature sensor **118**. The temperature sensor **118** and temperature regulating system **122** can be integrated and/or can be of a unitary construction. The temperature regulating system **122** can control the heating device **116**. The temperature regulating system **122** can control a fan **114**. The temperature regulating system **122** can control the fan **114** and the heating device **116**. For example, the temperature regulating system **122** can be used to control the heating device **116** to reach or maintain a nominal operating temperature while the fan **114** prevents the operating temperature from getting too high. This optimization can be used, for example, if the LED array **111** is not continuously on. The fan **114** can direct an air current over one or more cooling fins **104**. The cooling fins **104** can be in thermal contact with the LED array **110**, with the substrate **112**, or with both. The temperature regulating system **122** can send signals to and/or receive signals from the temperature sensor **118**, the heating device **116**, and/or the fan **114**. The temperature regulating system **122** can send and receive signals using wires **120**. Excitation beams can be emitted from LED array **110** and directed to one or more reaction region **108**. The reaction region **108** can include a sample **107**. The reaction region can be a microtiter tray.

[0025] **FIG. 2** is a side cross-sectional view of a system **200**, according to various embodiments, that includes a temperature stabilization device for an LED array **210**, for example, by including a plurality of LEDs **111**. A focal lens **206** can be included to focus excitation beams emitted from each of the individual LEDs **211**. The LED array **210** can be in physical and/or thermal contact with a substrate **212**. The system **200** can include a temperature sensor **218** in thermal contact with the LED array **210**, the substrate **212**, or both. The temperature sensor **218** can be included in or on the substrate **212**. A temperature regulating system **222** can receive a signal from the temperature sensor **218**. The temperature regulating system **222** can control a thermoelectric device **214**, for example, a Peltier device. The thermoelectric device **214** can be in thermal contact with the LED array **210**, with substrate **212**, or with both. The thermoelectric device **214** can transfer thermal energy from an ambient environment to the LED array **210**. The thermoelectric device **214** can transfer thermal energy to an ambient environment from the LED array **210**. The thermoelectric device **214** can include a temperature sensor. A plurality of cooling fins **204** can be in thermal contact with the LED array **210** and/or with the thermoelectric device **214**. The temperature regulating system **222** can send signals to and/or receive signal from the temperature sensor **218**, and/or the thermoelectric device **214**, for example, through wires **220**. Excitation beams can be emitted from LED array **210** and can be directed to a plurality of reaction regions **208**, for example, held in a thermal cycling block **230**. The thermoelectric device **214** can be used to maintain a lower temperature than could be otherwise achieved under operating conditions. This can permit the LED array **210** to operate more efficiently, with a higher total flux output. The thermoelectric device **214** can be used in a heating mode, for example, to reach or maintain a temperature when the LED array **210** is not on. The thermoelectric device **214** can be used in a cooling mode when the duty cycle of the LED array **210** is high enough to require cooling.

[0026] **FIG. 3*a*** is a side cross-sectional view of a system **300** according to various embodiments and capable of providing temperature stabilization for an LED array **310** including a plurality of individual LEDs **311**. A focal or collimating lens **306** can be included to focus excitation beams emitted from each of the individual LEDs **311**. The collimating lens can be a Fresnel lens. A beam splitter **307** can be included to separate excitation beams from emission beams. The beam splitter **307** can be replaced by a filter or beam splitter as described, for example, in U.S. patent application Ser. No. 10/735,339, filed Dec. 12, 2003, which is incorporated herein in its entirety by reference. The LED array **310** can be in contact with a substrate **312**. The system **300** can include a temperature sensor **318** in thermal contact with the LED array **310**. The temperature sensor **318** can be included in, on, or in and on the substrate **312**. A temperature regulating system **322** can receive a signal from the temperature sensor **318**. The temperature regulating system **322** can control a fan **314**. The fan **314** can direct an air current over a plurality of cooling fins **304**. The cooling fins **304** can be in physical and/or thermal contact with the LED array **310**. The temperature regulating system **322** can communicate with the temperature sensor **318**, and/or the fan, through wires **320**. Excitation beams can be emitted from LED array **310** and directed to a reaction region **308** formed or disposed in, on, or in and on a substrate **309**. The reaction regions can include capillaries **330** of a capillary array. The capillaries **330** can each have a portion that passes through a detection zone **356**.

[0027] According to various embodiments, the temperature control system can include a heater. The system can include a cooler. The system can include both a heater and a cooler. Cooling and heating rates can be augmented by using a plurality of heaters and/or coolers as desired. If a heater is provided, it can comprise a plurality of different types of heating devices. If a cooler is provided, it can comprise a plurality of different types of cooling devices.

[0028] **FIG. 3*b*** is a top plan partial view of the array of capillaries **330** shown in **FIG. 3*a***, and the detection zone **356**. The capillaries can traverse the detection zone **356**, where excitation beams from the LED array **310** **(FIG. 3*a*)** can be directed. For example, the excitation beams can be used for fluorescence detection of analytes in capillaries of a capillary electrophoresis device. Such can be the case in DNA sequencing and fragment length analysis applications.

[0029] An LED illumination system can provide consistent illumination, can be light in weight, and can require minimal cooling and/or heating. The LED can be a standard semi-conductor device, an organic LED, or an inorganic LED. Examples of organic LEDs are QDOT-based LEDs and a nanotube-based LEDs. The LED can be a stack of LED's such as a stack of organic LEDs or a stack of organic LED layers.

[0030] According to various embodiments, LEDs producing several different excitation wavelengths can be used, either simultaneously or sequentially. The use of a plurality of different excitation wavelengths can improve the calibration matrix necessary to distinguish fluorescence emissions of various dyes.

[0031] According to various embodiments, a system can comprise LEDs, photodiodes, operational amplifiers, and LED-current control circuits. The components of the system can change properties with operating temperature variations. A temperature regulating system can maintain these components at a constant temperature. The constant temperature can be elevated from an ambient temperature. The constant temperature can be lower than an ambient temperature. For example, the system components can be held at a constant temperature above an ambient temperature using a resistive heating element as a heat source under the control of the temperature regulating system. A strong or high thermal conductivity pathway can be used between the system components, for example, to the temperature sensor from a heat source and/or a heat sink.

[0032] The temperature sensor can be used to measure directly, indirectly, or by calculation, the temperature of the system components. The temperature sensor can measure an operating temperature for various components of the system. The temperature sensor can provide feedback to a temperature regulating system. The temperature regulating system can monitor the amount of heating or cooling provided by a heat source or a heat sink to maintain the system components at a nominal temperature within an acceptable deviation value range.

[0033] The temperature control characteristics of a temperature regulating system can be improved by enclosing the system components in a thermally isolated environment. For example, the system components and the temperature sensor, and/or the temperature regulating system, can be placed in an enclosure or housing. The enclosure can have openings for allowing illumination from the LEDs to illuminate a detection zone. Heat exchange pathways can be disposed in the enclosure to allow for thermal transfer between the system and an ambient environment. The heat exchange pathway can be a vent in the enclosure. A cooling fan can cool the thermally isolated environment provided by the enclosure. The heat exchange pathway can include, for example, a high conductivity thermal surface included in the enclosure and in thermal contact with a thermoelectric device. The system components can be separated from the enclosure using a thermal insulator to lower a heat exchange rate between the enclosure and the temperature control components. The temperature sensor can be in thermal contact with, in heat-transfer communication with, or otherwise thermally coupled to, the substrate. Known methods of heat transfer include, but are not limited to conduction, convection, and thermal radiation.

[0034] According to various embodiments, a heat conductive adhesive or compliant pad can be used to attain good thermal conductivity between a heat sink or heat source, and other system components, for example, to maintain temperature stability in the system. A heat exchange pathway can be established for system components such as photodiodes and LEDs using a ground path to the same metal or layer plate, for example, in a PCB. The plate can be a metal, for example, aluminum, copper, or other electrically conductive metals. The system can thus maintain temperature stability and keep various system components at substantially the same temperature. The heat exchange pathway can exchange heat with the ground plate. Other temperature interface materials, for example, adhesive backed resistive elements, can be used to achieve good contact with the system components. A resistive heater can be disposed in or on a common substrate shared with other electrical circuits included in the system.

[0035] **FIG. 4** is a top plan cross-sectional view of a system **400**. A housing **401**, also known as a cave, an oven, or an enclosure, can include openings such as **403** and **407** as shown. LEDs **413**, **415** can irradiate through respective openings **(403)** to illuminate one or more reaction regions (not shown). The opening **407** can allow transmission or passing of emission beams from a reaction region to a detector **440**. One or more temperature sensor **418** can be disposed in or on a housing substrate **412**. The substrate **412** can include a heating device **416**. The temperature sensor **418** can be disposed on or in the housing substrate **412**. LEDs **413** and **415**, and detector **440**, can be disposed on or in the housing substrate **412**. A temperature regulator or temperature regulating system **422**, capable of receiving a signal from the temperature sensor **418**, can be included, for example, in the housing **412**. The temperature regulating system **422** can control the heating device **416** and/or a cooling fan **414**, as desired, for example, to maintain the system **400** within a desired or pre-set temperature range. The housing **401** can provide a relatively small, thermally isolated, volume to be temperature-regulated by the temperature regulating system **422**. Control circuits (not shown) necessary to utilize the LEDs **413**, **415** and the detector **440** can be housed within the housing **401**. Excitation beams can be emitted from the LEDs **413**, **415** and directed toward one or more reaction regions. LED **413** can produce excitation beams of a different wavelength range than LED **415**, for example, LED **413** can produce blue light and LED **415** can produce green light. LED **413** can be operated simultaneously or sequentially with LED **415**.

[0036] **FIG. 5** is a side cross-sectional view of a system **500** according to various embodiments. The system **500** can include photodiode detectors **550**, **552**, and **554** disposed on a substrate **574**. The substrate **574** can have control circuits **560**, **562**, **564**, and **566** disposed on a first surface or back side **575** thereof. The system **500** can include an LED **513** mounted on a plate **568** having a thermal conductivity of about 0.1 w/cm·k or higher, for example, about 0.3 w/cm·k or higher or about 0.5 w/cm·k or higher. For example, the plate **568** can comprise, for example, aluminum, steel, stainless steel, another metal or alloy, a printed circuit board, or a combination thereof. An elastomer pad **570** having a high thermal conductivity can be disposed between the substrate **574** and the plate **568**. The substrate can be a multi-layer structure including a layer having a thermal conductivity of about 0.1 w/cm·k or higher. The elastomer pad **570** can electrically isolate an electric resistive heater **518** from the substrate **574**. The photodiode detectors **550**, **552**, and **554** can be adhered or bonded to the substrate **574** using, for example, an adhesive **572**. A temperature sensor **519** can be disposed in thermal contact with the system **500**, for example, the temperature sensor **519** can be disposed in contact with the plate **568**. Thermal insulation **576** can be disposed adjacent the second surface or backside **575** of the substrate **574** to thermally isolate the system **500** from an ambient environment. The system can maintain the control circuits **560**, **562**, **564**, **566**, the photodiode detectors **550**, **552**, **554**, and the LEDs **511**, **513**, at the same temperature. Accordingly, a constant and uniform temperature can be maintained across the system **500**.

[0037] Various embodiments depicting configurations of LED's, reaction regions, and intervening devices that can be used to direct excitation beams from light sources, for example, LEDs, toward reaction regions, can be found, for example, in U.S. patent application Ser. No. 10/440,920, filed May 19, 2003, entitled "Optical Instrument Including Excitation Source" to Boege et al., U.S. patent application Ser. No. 10/440,719, filed May 19, 2003, entitled "Optical Instrument Including Excitation Source" to Boege et al., U.S. patent application Ser. No. 10/440,852, filed May 19, 2003, entitled "Apparatus And Method For Differentiating Multiple Fluorescence Signals By Excitation Wavelength" to King et al., U.S. patent application Ser. No. 10/735,339, filed Dec. 12, 2003, and International Publication No. PCT/US01/35079. All Patents, Patent Applications, and publications mentioned herein are incorporated herein in their entireties by reference.

[0038] The LED or the LED array can include a plurality of LEDs mounted on a substrate. The LED can thermally contact a temperature regulating system. The temperature regulating system can control a heat-transfer device and/or a temperature sensor. The temperature regulating system can maintain the operating temperature of the LED such that the operating temperature does not change appreciably, by not more than 0.5° C., that is, does not fluctuate by more than 10° C. during operation, for example, by not more than 5° C., by not more than 1° C., by not more than 0.5° C., or by not more than 0.1° C. or less. The temperature regulating system can maintain the operating temperature of the LED such that the operating temperature does not exceed the bounds of a programmed temperature range. According to various embodiments, a temperature regulating system and a temperature sensor can be included in a single-unit or can be included in an integrated device, for example, a Maxim DS1620 device available from Maxim Integrated Products, Inc. of Sunnyvale, Calif.

[0039] The temperature sensor and the LED do not necessarily have to be in physical contact. The temperature regulating system can adjust a monitored temperature of the LED to compensate for any thermal masses intervening between the LED and the temperature sensor and to thus derive, calculate, or estimate an operating temperature.

[0040] According to various embodiments, the LED can be cooled to maintain life and illumination uniformity requirements of a system. According to various embodiments, a forced air cooling system or a thermoelectric device, for example, a Peltier device, can be used to cool the LED and to keep the LED from exceeding a maximum operating temperature.

[0041] According to various embodiments, the temperature of the LED can be monitored, for example, with a temperature sensor, and thermal characteristics of a system and spectral characteristics of any LEDs embedded within the system, can be recorded. With understanding and reproducibility of the spectral coefficients of the LED as a function of an operating temperature, the effects of a spectral shift can be mitigated upon detection of optical properties of a sample. According to various embodiments, a dye matrix or detection data can be altered in accordance with the conditions under which the dye matrix or detection data was gathered or detected. Thermal effects on excitation beams emitted by LEDs, including spectral shifts and intensity changes, can thus be minimized or effectively eliminated. According to various embodiments, the temperature of an LED can be monitored and a computing apparatus can adjust the detection data to compensate for the spectral shifts and/or intensity changes of excitation beams emitted from the LED. The compensation for the shifting can be varied across wavelength ranges, for example, different compensations can be provided for different wavelengths of LEDs. A system can be provided that can include a data adjustment unit comprising a memory adapted to store at least two operating temperatures and at least one respective excitation beam characteristic shift for each operating temperature. A plurality of respective excitation beam characteristic shifts can be stored in the memory. The adjustment data can be in the form of a plurality of respective coefficients. Each coefficient can correspond to a respective LED of an LED array. An exemplary range of coefficients can be from about 0.4 nm/° C. to about 4.0 nm/° C., for example, based on deviation from a set or average operating temperature. The coefficients can include two or more nominal temperature coefficients corresponding to two or more LEDs. The coefficients can be determined or designated based on the position of a respective LED in an LED array.

[0042] According to various embodiments, optical detection instruments utilizing LEDs can obtain very stable intensity or spectral characteristics by stabilizing an operating temperature of an LED. Illumination stability can be important to minimize the signal noise in the system. Illumination stability can improve the sensitivity of the instrument to detect low concentration dyes. Spectral stability can be used to maintain values for the deconvolution matrix associated with a set of dyes to prevent quantification errors. Similarly, variations in intensity resulting from temperature changes can be different for different wavelengths of LEDs, resulting in apparent spectral instability.

[0043] According to various embodiments, illumination stability can be improved by allowing the illumination source to warm-up. According to various embodiments, shutters can block excitation beams from reaching a sample to prevent bleach out. According to various embodiments, shutters can block excitation beams from reaching a sample to prevent bleach out during illumination source warm-up. The illumination source can be brought to a desired operating temperature range prior to enabling or turning on the illumination source, using a heater and/or a cooler. Regulating the temperature of the illumination source prior to enabling the illumination source can prevent the need for a shutter and/or can reduce the warm-up time period. According to various embodiments, samples can be subjected to a reaction or a series of reactions, for example, temperature cycled in a nucleic acid sequence amplification or in a sequencing process. According to various embodiments, the shutter can be unblocked in co-ordination with the reaction or the series of reactions, to detect and collect data at an appropriate time, for example, during a fluorescence detection reading of the sample.

[0044] According to various embodiments, sensitivity of the instrument to detect low concentration dyes can be used. An LED can shift, for example, 5% over a 15° C. ambient temperature range maintained by some optical instrumentation. According to various embodiments, a spectral shift of an LED can vary depending on a center wavelength of the LED, for example, blue LEDs can shift less than red LEDs. The spectral shift can be from about 0.04 nm/° C. to about 0.4 nm/° C. The spectral shift can be different for different temperatures. The spectral shift can be calculated. The spectral shift can be obtained from a look-up table. The table can be sorted by temperature, for example. The table can be provided in a long-term storage of a computer system, for example. According to various embodiments, some optical instrumentation can be sensitive to a dye shift of about 1 nm or less. According to various embodiments, laboratory instrumentation utilizing a relatively more robust dye matrix can be less susceptible to the spectral shift of an LED than a system with a relatively less robust dye matrix. The AB **7500** system available from Applied Biosystems of Foster City, Calif., can have a very good dye matrix and can have little susceptibility to spectral shift for at least most dyes.

[0045] According to various embodiments, the LED radiation source can contain one Light Emitting Diode (LED) or an array of individual LEDs. According to various embodiments, each LED can be a high power LED that can emit greater than or equal to about 1 mW of excitation energy. In various embodiments, a high power LED can be used that can emit at least about 5 mW of excitation energy. In various embodiments wherein the LED or array of LEDs can emit, for example, at least about 50 mW of excitation energy, a cooling device such as, but not limited to, a heat sink or fan can be used with the LED. An array of high-powered LEDs can be used that draws, for example, about 10 watts of energy or less, about five watts of energy or less, or about 3 watts of energy or less. Exemplary LED array sources are available, for example, from Stocker Yale (Salem, N.H.) under the trade name LED AREALIGHTS, and from Lumileds Lighting, LLC (San Jose, Calif.) under the trade name Luxeon Star. According to various embodiments, LED light sources can use about 1 microwatt (μW) of power or more, for example, about 5 mW, about 25 mW, about 50 mW, about 1 W, about 5 W, about 50 W, or about 100 W or more, each individually or collectively when used in an array.

[0046] According to various embodiments, the light source can include a combination of two, three, or more

LEDs, laser diodes, and the like, such as, for example, an LED that can emit radiation at about 475 nm, an LED that can emit radiation at about 539 nm, and an LED that can emit radiation at about 593 nm. The LED can be, for example, an Organic Light Emitting Diode (OLED) an inorganic Light Emitted Diode, that can be polymer-based or small-molecule-based (organic or inorganic), an edge emitting diode (ELED), a Thin Film Electroluminescent Device (TFELD), or a Quantum dot based inorganic "organic LED." The LED can include a phosphorescent OLED (PHOLED). Super bright LEDs can be used and can be arranged in a light array. According to various embodiments, separate LEDs or a packaged set of LEDs can be used in an array. Spectral emissions of the light sources can be effected by an operating temperature of the light source. Other suitable light sources will be apparent to practitioners in the art given the teachings herein. OLEDs can be used as an array while being designed as a single part. As used herein, the terms "excitation source,""irradiation source," and "light source" are used interchangeably.

[0047] According to various embodiments, excitation beams emitted from the light source can diverge from the light source at an angle of divergence. The angle of divergence can be, for example, from about 5° to about 75° or more. The angle of divergence can be substantially wide, for example, greater than 45°, yet can be efficiently focused by use of a lens, such as the focusing lens **106 (FIG. 1)**, **206 (FIG. 2)**, and **306 (FIG. 3)**. The lens can be a collimating lens, for example, a Fresnel lens.

[0048] According to various embodiments, a quantum dot can be used as a source for luminescence and as a fluorescent marker. Quantum dots can be used for both. The quantum dot based LED can be tuned to emit light in a tighter emission bandpass, for example, an emission bandpass including a full-width of half-max of about 10 nm or less, about 20 nm or less, or about 50 nm or less. The quantum dot based LED can increase the efficiency of the fluorescent system. The efficiency of a quantum dot based LED can theoretically be higher than that of conventional LEDs, potentially over 90% when sandwiched directly between two conductive films with each film directly touching each quantum dot as opposed to the present 20% efficiency for standard LEDs. Quantum dot based LEDs can be made utilizing a slurry of quantum dots, where current flows through an average of several quantum dots before being emitted as a photon. This conduction through several quantum dots can cause resistive losses in efficiency. Quantum dots can provide many more colors than conventional LEDs.

[0049] A Quantum dot based LED can emit light in an emission band that is narrower than an emission band of a normal LED, for example, about 50% narrower or about 25% narrower. The emission band of the quantum dots can be a function of the size distribution of the quantum dots, and thus can theoretically be extremely narrow. The Quantum dot based LED can also emit light at an electrical energy conversion efficiency of about, 90% or more, for example, approaching 100%. OLED films, including Quantum dot based LEDs, can be applied to a thermal block, used for heating and cooling samples, in a fluorescence system without interfering with the operation of the thermal block.

[0050] According to various embodiments, an OLED can be used and/or produced on a flexible substrate, on an optically clear substrate, on a substrate of an unusual shape, or on a combination thereof. Multiple OLEDs can be combined on a substrate, wherein the multiple OLEDs can emit light at different wavelengths. Multiple OLEDs on a single substrate or multiple adjacent substrates can form an interlaced or a non-interlaced pattern of light of various wavelengths. The pattern can correspond to, for example, a sample reservoir arrangement or array. One or more OLEDs can form a shape surrounding, for example, a sample reservoir, a series of sample reservoirs, an array of a plurality of sample reservoirs, or a sample flow path. The sample flow path can be, for example, a channel, a capillary, or a micro-capillary. One or more OLEDs can be formed to follow the sample flow path. One or more OLEDs can be formed in the shape of a substrate or a portion of a substrate. For example, the OLED can be curved, circular, oval, rectangular, square, triangular, annular, or any other geometrically regular shape. The OLED can be formed as an irregular geometric shape. The OLED can illuminate one or more sample reservoirs, for example, an OLED can illuminate one, two, three, four, or more sample reservoirs simultaneously, or in sequence. The OLED can be designed, for example, to illuminate all the wells of a corresponding multi-well array.

[0051] According to various embodiments, an OLED can be used and can be formed from one or more stable, organic materials. The OLED can include one or more carbon-based thin films and the OLED can be capable of emitting light of various colors when a voltage is applied across the one or more carbon-based thin films. Various LEDs can use different films, for example, quantum dot based LEDs can use Indium tin oxide.

[0052] According to various embodiments, an operating temperature of an LED can be controlled with a Peltier-effect thermoelectric device, a heat pump, an electrical resistance heating element (Joule heater), fluid-flow through channels in a metal block, reservoirs of fluid at different temperatures, tempered air impingement, a combination thereof, or the like. According to various embodiments, the thermal device can include a fan to direct air-flow over cooling fins, or a cold bar to assist in a heat transfer between an LED and another thermal mass, such as air. According to various embodiments, the thermal conductivity of the LED and/or a platform supporting the LED can be greater than that of a surrounding ambient environment, for example, the surrounding air.

[0053] According to various embodiments, a thermoelectric device can be used as a heat-transfer device, for example, an XLT module available from Marlow Industries, Inc. of Dallas, Tex. Controls for the thermoelectric device can include an adjustable-bipolar DC output current power supply. The power supply can provide programmable PID control/ramp to set point control, deviation alarms, and automatic and manual operating modes. In reactions, for example, real-time monitoring of Polymerase Chain Reaction (PCR) reactions, thermoelectric devices can both heat and cool, as desired, the LED by using a bi-directional power supply under programmable and/or logic control. The programmable and logic control can be provided by using a general purpose computer, or custom built hardware, for example, a field programmable gate array (FPGA). Thermoelectric devices can be specifically designed to withstand the continuous temperature excursions required in PCR use.

[0054] According to various embodiments, a heat-transfer device can include a vapor-cycle device, for example, a Freon-based vapor compression or absorption refrigerator. In such units, thermal energy can be extracted from a region, thereby reducing its temperature, then rejected to a "heat sink" region of higher temperature. Vapor-cycle devices can include moving mechanical parts and can include a working fluid, while thermoelectric elements can be totally solid state.

[0055] According to various embodiments, a thermal interface material (TIM) can provide a good thermal contact between two surfaces, for example, between an LED support and a substrate, and/or between an LED housing and a thermoelectric device. The TIM can include silicone-based greases, elastomeric pads, thermally conductive tapes, thermally conductive adhesives, or a combination thereof. Zinc-oxide silicone can be used as a TIM. According to various embodiments, Gap-Pad products, for example, GAP PAD VO ULTRA SOFT materials or SIL-PAD, materials available from Berquist Company of Chanhassen, Minn., can be used as thermal interface materials. A TIM is described in U.S. Pat. No. 5,679,457 to Bergerson, which is incorporated herein in its entirety. According to various embodiments, a TIM can be disposed between a heat-transfer device and an LED.

[0056] According to various embodiments, a method can be provided for maintaining emssion intensity and spectral stability of an LED. The method can comprise: providing a system comprising an LED; generating excitation beams with the LED; measuring an operating temperature of the LED; and regulating the operating temperature by at least one of transferring heat from the LED and transferring heat to the LED, based on the operating temperature, to maintain emssion intensity and spectral stability of the LED. The regulating can comprise retrieving from a memory source adjustment data corresponding to a desired operating temperature or temperature range at which emission intensity and spectral stability of the LED are maintained.

[0057] Other embodiments will be apparent to those skilled in the art from consideration of the present specification and practice of various embodiments disclosed herein. It is intended that the present specification and examples be considered as exemplary only.

What is claimed is:

1. A system comprising:

a light-emitting diode (LED);

a temperature sensor in thermal contact with the LED and capable of measuring an operating temperature of the LED and generating an operating temperature signal; and

a temperature regulating system capable of receiving the operating temperature signal and regulating the operating temperature based on the operating temperature signal, and adapted to control excitation of one or more fluorescent dyes.

2. The system of claim 1, wherein the temperature sensor and the temperature regulating system comprise a single unit.

3. The system of claim 1, wherein the temperature regulating system includes a heat-transfer device and a control unit capable of controlling the heat-transfer device.

4. The system of claim 3, wherein the heat-transfer device includes a fan capable of forming an air current in thermal contact with the LED.

5. The system of claim 3, wherein the heat-transfer device includes one or more cooling fins in thermal contact with the LED.

6. The system of claim 3, wherein the heat-transfer device includes a heater in thermal contact with the LED.

7. The system of claim 3, wherein the heat-transfer device includes a thermoelectric device in thermal contact with the LED.

8. The system of claim 7, wherein the heat-transfer device includes a reversible power supply capable of supplying power to the thermoelectric device.

9. The system of claim 1, wherein the temperature regulating system is capable of increasing the operating temperature of the LED.

10. The system of claim 1, wherein the temperature regulating system is capable of decreasing the operating temperature of the LED.

11. The system of claim 1, wherein the temperature regulating system is capable of maintaining the operating temperature to be within an operating temperature range including a minimum temperature and a maximum temperature separated by about 5° C.

12. The system of claim 1, wherein the temperature regulating system is capable of maintaining the operating temperature to be within an operating temperature range including a minimum temperature and a maximum temperature separated by about 1° C.

13. The system of claim 1, further comprising a user input device in communication with the temperature regulating system and capable of inputting an operating temperature range including a nominal temperature and an acceptable deviation value rage.

14. The system of claim 1, wherein the temperature sensor comprises at least one of a thermistor, a thermocouple, a bandgap semiconductor resistive temperature detector, a platinum resistive temperature detector, or a bi-metallic temperature detector.

15. The system of claim 1, wherein the temperature sensor comprises at least one of a thermistor, or a bandgap semiconductor resistive temperature detector.

16. The system of claim 1, further comprising an error signaling device capable of signaling an alarm when at least one condition of (1) the operating temperature is greater than a maximum temperature, and (2) the operating temperature is less than a minimum temperature, is met.

17. The system of claim 1, further comprising a substrate contacting the LED.

18. The system of claim 17, wherein the substrate has a thermal conductivity of about 0.1 w/cm·k or greater.

19. The system of claim 17, wherein the LED comprises a plurality of LED's.

20. The system of claim 17, wherein the substrate is a multi-layer laminate and at least one layer of the laminate has a thermal conductivity of about 0.1 w/cm·k or greater.

21. The system of claim 17, wherein the substrate includes a printed-circuit board.

22. The system of claim 1, wherein the LED includes an organic LED.

23. The system of claim 1, wherein the LED includes a quantum-dot based light source.

24. The system of claim 1, wherein the LED comprises a plurality of light-emitting diodes that are capable of emitting emissions of different respective wavelength ranges.

25. The system of claim 24, wherein the plurality of LEDs comprises at least one Blue LED and at least one Green LED.

26. The system of claim 1, further comprising a reaction region, and wherein the LED is capable of generating and directing excitation beams toward the reaction region.

27. The system of claim 26, wherein the reaction region comprises a plurality of spaced-apart reaction regions.

28. The system of claim 26, wherein the reaction region comprises a sample disposed therein, and the sample comprises at least one nucleic acid sequence.

29. The system of claim 26, further comprising a detector capable of detecting at least one optical property of the reaction region.

30. The system of claim 26, wherein the reaction region includes at least one nucleic acid sequence amplification reaction reagent.

31. The system of claim 1, further comprising at least one separation region, and wherein the LED is capable of generating and directing excitation beams toward the at least one separation region.

32. The system of claim 31, wherein the LED comprises a plurality of light-emitting diodes that are capable of emitting different respective wavelength ranges.

33. The system of claim 31, wherein the at least one separation region comprises an electrophoresis separation medium.

34. The system of claim 1, wherein the reaction region includes at least one fluorescent reporter dye.

35. A system comprising:

a reaction region;

a light-emitting diode (LED) capable of generating and directing excitation beams toward the reaction region;

a temperature sensor in thermal contact with the LED and capable of measuring an operating temperature of the LED and generating an operating temperature signal;

a detector adapted to detect emission signals from the reaction region and capable of generating detection data; and

a data adjustment unit capable of receiving the operating temperature signal and the detection data, and adapted to adjust the detection data for an excitation beam characteristic shift related to the operating temperature, to form shifted detection data.

36. The system of claim 35, wherein the data adjustment unit comprises a memory adapted to store at least two operating temperatures and at least one respective excitation beam characteristic shift for each operating temperature.

37. The system of claim 35, wherein the temperature sensor comprises at least one of a thermistor, a thermocouple, a bandgap semiconductor resistive temperature detector, a platinum resistive temperature detector, or a bi-metallic temperature detector.

38. The system of claim 35, wherein the LED comprises a plurality of light-emitting diodes that are capable of emitting different respective wavelength ranges.

39. The system of claim 38, wherein the data adjustment unit comprises a memory adapted to store at least two operating temperatures, and at least one respective excitation beam characteristic shift for each operating temperature, and wherein the at least one respective excitation beam characteristic shift comprises at least one respective excitation beam characteristic shift for each different wavelength range.

40. The system of claim 38, wherein the plurality of LEDs comprises at least one blue LED and at least one green LED.

41. The system of claim 35, further comprising at least one separation region, and wherein the LED is capable of generating and directing excitation beams toward the at least one separation region.

42. The system of claim 35, wherein the LED comprises a plurality of LEDs disposed adjacent one another and each LED has a respective operating temperature and a respective excitation beam characteristic shift.

43. The system of claim 35, wherein the LED comprises a plurality of LEDs stacked along a path for directing excitation beams towards the reaction region, and each LED has a respective operating temperature and a respective excitation beam characteristic shift.

44. The system of claim 35, further comprising a temperature regulating system capable of receiving the operating temperature signal and regulating the operating temperature based on the operating temperature signal.

45. The system of **35**, wherein the excitation beam characteristic comprises a spectrum of the generated excitation beams.

46. The system of **35**, wherein the excitation beam characteristic comprises an intensity of the generated excitation beams.

47. A method for illuminating a reaction region with excitation beams, the method comprising:

providing a system comprising an LED, a reaction region, and a sample in the reaction region;

generating excitation beams with the LED;

directing excitation beams at the sample;

measuring an operating temperature of the LED; and

regulating the operating temperature by at least one of transferring heat from the LED and transferring heat to the LED, based on the operating temperature.

48. The method of claim 47, wherein said regulating the operating temperature includes maintaining the operating temperature to be within an operating temperature range including a minimum temperature and a maximum temperature separated by about 5° C.

49. The method of claim 47, wherein said regulating the operating temperature includes maintaining the operating temperature to be within an operating temperature range including a minimum temperature and a maximum temperature separated by about 1° C.

50. The method of claim 47, wherein said regulating the operating temperature occurs prior in time to said generating the excitation beams.

51. The method of claim 47, wherein said regulating the operating temperature comprises setting the operating temperature to be greater than an ambient environment temperature.

52. The method of claim 47, wherein the sample includes reagents necessary to perform a nucleic acid sequence amplification reaction.

53. The method of claim 47, wherein the LED comprises a plurality of light-emitting diodes that are capable of emitting different respective wavelength ranges.

54. A method for illuminating a reaction region with excitation beams, the method comprising:

providing a system comprising an LED, a reaction region, and a sample in the reaction region;

generating excitation beams with the LED;

directing excitation beams to the sample;

detecting an optical property of the sample to obtain detection data;

measuring the operating temperature of the light emitting diode to determine a measured temperature; and

adjusting the detection data of an excitation beam characteristic shift related to the measured temperature.

55. The method of **54**, wherein the excitation beam characteristic comprises a spectrum of the generated excitation beams.

56. The method of **54**, wherein the excitation beam characteristic comprises an intensity of the generated excitation beams.

57. The method of claim 54, wherein the sample includes reagents necessary to perform a nucleic acid sequence amplification reaction.

58. The method of claim 54, wherein the LED comprises a plurality of light-emitting diodes that are capable of emitting different respective wavelength ranges.

59. The method of claim 58, adjusting the detection data comprises picking the excitation beam characteristic shift based on the position of an activated LED from the plurality of LEDs.

60. The method of claim 54, wherein the LED comprise a plurality of LEDs disposed adjacent to one another and each LED has a respective operating temperature and a respective excitation beam characteristic shift.

61. The method of claim 60, wherein the LED's comprise inner LEDs and outer LEDs, and the method comprises making a greater adjustment of excitation beam characteristic shift for one or more of the inner LEDs compared to the adjustment for one or more of the outer LED's.

62. The method of claim 60, wherein adjusting the detection data comprises retrieving from a memory source a respective excitation beam characteristic shift.

63. The method of claim 54, wherein the LED comprises a plurality of LEDs stacked in along a path for directing excitation beams towards the reaction region and each LED has a respective operating temperature and a respective excitation beam characteristic shift.

64. The method of claim 54, further comprising profiling the plurality of LEDs to obtain a calculated operating temperature based on a position of each LED in the plurality of LEDs.

65. A method for maintaining emission intensity and spectral stability of an LED, the method comprising:

providing a system comprising an LED;

generating excitation beams with the LED;

measuring an operating temperature of the LED; and

regulating the operating temperature by at least one of transferring heat from the LED and transferring heat to the LED, based on the operating temperature, to maintain emssion intensity and spectral stability of the LED.

66. The method of claim 65, wherein the regulating the operating temperature comprises retrieving from a memory source adjustment data corresponding to a desired operating temperature or temperature range at which emission intensity and spectral stability of the LED are maintained.

* * * * *

Red, Green, and Blue LEDs for White Light Illumination

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***Abstract*—The rapid improvement of the white light efficacy achievable with light-emitting diodes (LEDs) opens up new opportunities in the general illumination market. An LED light source made of red, green, and blue LEDs (RGB-LEDs) can provide the unique feature of color variability, allowing the user to select the desired color point of the lamp. The white light color accuracy required in the general illumination market is a challenge for LEDs. The variation in lumen output and wavelength for nominally identical LEDs and the change in these parameters with temperature and time result in an unacceptably high variability in the color point of white light from RGB-LEDs.**

In this paper, we show that these problems can be overcome with suitable feedback control schemes that can be implemented in a practical LED lamp. We present results of experiment and theoretical modeling that shows the performance that can be achieved with a number of different control schemes.

***Index Terms*—Color accuracy, feedback control, light-emitting diodes, white light illumination.**

I. INTRODUCTION

THE RAPID development of light-emitting diodes (LEDs) over the last few years has opened up new opportunities in the general illumination market [1]. The efficacy of white light from LEDs is now over 20 lm/W, which already exceeds that of incandescent lamps [2]. By 2005, it is forecast that LED efficacy will reach 50 lm/W [3], which approaches that of compact fluorescent lamps. In addition, higher power packages are becoming available that enable compact lighting systems with LEDs. However, additional challenges remain. The general illumination market has strict requirements on the quality of white light—lamps of the same type must all appear to have the same color point. In this paper, we discuss these requirements, the issues with LEDs that make these requirements a challenge, and how to meet these requirements.

There are several approaches using LEDs to achieve white light [4]. One approach is to use a blue or UV LED to excite one or more phosphors to give white light. In this paper, we focus on the use of red, green, and blue LEDs (RGB-LEDs) to produce white light. The advantages of RGB-LEDs are that they provide a light source that can have a variable color point, and theoretically can provide the highest efficiency LED-based white light. The ability to change the color point of the lamp provides a new feature to general illumination that has the potential to generate new applications and hence new market opportunities.

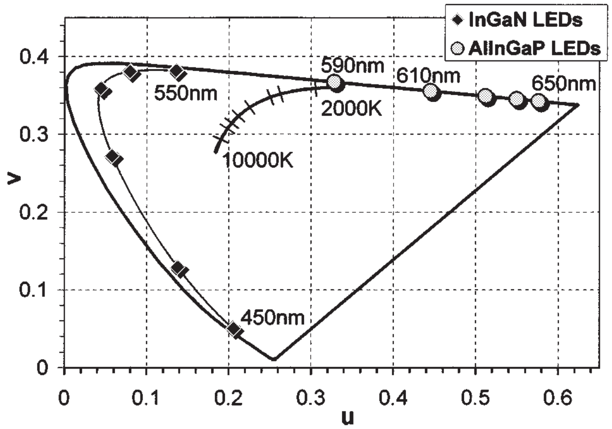

Fig. 1. The 1964 CIE (u, v) coordinate system showing the coordinates of InGaN and AlInGaP LEDs. Also shown is the blackbody line over a range of color temperatures from 2 000 K to 10 000 K.

A key challenge for RGB-LEDs is to maintain the desired white point within acceptable tolerances. This arises from the significant spread in lumen output and wavelength of manufactured LEDs, and the changes in LED characteristics that occur with temperature and time. Maintaining the desired white point can only be achieved with feedback schemes to control the relative contributions of red, green, and blue to the white light.

II. WHITE LIGHT REQUIREMENTS

It is well known that red, green, and blue LEDs can be combined to produce white light. This can be represented on a chromaticity diagram. The most common chromaticity diagram is the CIE 1931 coordinate system (xy) [5]. However, the just noticeable color difference is not a constant length over xy space. By applying a linear transformation a new coordinate space can be generated where the just noticeable color difference is approximately uniform. A number of such transformations exist. For the purposes of this paper we use the CIE 1960 UCS system (uv), as shown in Fig. 1. By combining three different color LEDs, it is possible to produce any color point ((u, v) coordinate) that lies within the triangle formed by the (u, v) coordinates of the three LEDs. In almost all white light illumination applications, the resultant color point must lie on, or very close to the locus of points that follows the line of a black-body radiator (shown in Fig. 1). An incandescent lamp has a black-body temperature of approximately 2700 K. Most fluorescent lamps are designed to have a color temperature of between 3000 K and 5000 K, dependent on the application and preference of the user.

Another key requirement of illumination relates to the spectral properties of the white light source. Our perceived color of objects depends upon the spectrum of incident light upon them.

Manuscript received December 11, 2001; revised January 23, 2002.

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Publisher Item Identifier S 1077-260X(02)03763-2.

TABLE I
VALUES OF COLOR RENDERING INDEX (R_a) REQUIRED FOR A NUMBER OF ILLUMINATION APPLICATIONS.

Indoor retail	R_a 90+
Indoor office / home	R_a 80
Indoor work area	R_a 60
Outdoor pedestrian area	R_a 60+
Outdoor general illumination	R_a 40-

TABLE II
VALUES OF COLOR RENDERING INDEX (R_a) THAT CAN BE ACHIEVED WITH THE COMBINATION OF TWO, THREE, AND FOUR DIFFERENT WAVELENGTH LEDs.

500nm + 595nm	R_a 40
470nm + 540nm + 610nm	R_a 80+
465nm + 535nm + 590nm + 625nm	R_a 90+

A red object illuminated with light that is drastically deficient in red will appear black. The lighting industry uses a standard color rendering index (R_a) to determine the color rendition properties of a light source. It is based on the components of eight standard spectra in the white light source as compared to a black-body radiator with the same color temperature as the light source. Thus, an incandescent lamp has an R_a value of 100. Typical fluorescent lamps used in offices have an R_a of 80. The required R_a value depends upon the application. Typical examples are given in Table I.

The illumination of goods in a retail store is typically the most demanding application for color rendering index. The precise requirements depend upon the goods being displayed. As the goods on display are changed, different color points may be desired. With conventional light sources, this means that the lamp has to be changed. RGB-LEDs will allow the desired color point to be achieved simply by adjusting the ratio of RGB illumination. Typical indoor living space is illuminated with sources that have an R_a of 80. The color temperature can vary from 2700 K with incandescent lamps, to the 4000 K typically used in offices with fluorescent lighting. RGB-LEDs will allow one lamp to provide a range of color temperatures. General outdoor illumination such as street lighting puts the lowest demands on color rendering with R_a of 40 or less being common.

The R_a that can be achieved with LEDs depends on the white spectrum. The white spectrum is made up of the individual LED spectra, and thus, depends on the wavelengths selected, and the number of different wavelength LEDs used to make white light. Table II shows the R_a values that can be achieved with the mixing of two, three, and four different wavelength LEDs.

RGB-LEDs can achieve the required R_a values provided that the correct LED wavelengths are selected. Most applications can be addressed by the selection of three different wavelengths.

A major requirement of many illumination applications is that the light source has the required color point (i.e., (u, v) coordinate), and that it stays at its color point over time. It is viewed as unacceptable if all fluorescent lamps lighting in an office area are not the same color. This raises the question: what is the required specification? There is no single answer—it depends upon the application. To quantify the color error of a light source, we introduce the quantity Δuv where

$$\Delta uv = ((u - u_o)^2 + (v - v_o)^2)^{0.5}$$

(u, v) being the color coordinates of the light source, and (u_o, v_o) are the required color coordinates. This is simply the distance in (u, v) color space of the lamp from the desired color point (see Fig. 1). As a point of reference, fluorescent tubes are usually specified to be within $\Delta uv = 0.003$ of their designed color point. Some discharge lamps have larger deviations of over $\Delta uv = 0.01$, and are regarded as unacceptable by some customers. As we will show below, the demands on color reproducibility of the general illumination market provides a severe challenge for RGB-LEDs. Color point reproducibility is also a severe challenge for most approaches to phosphor-LEDs. No phosphor-LEDs on the market today meet the color point reproducibility requirements of the general illumination market.

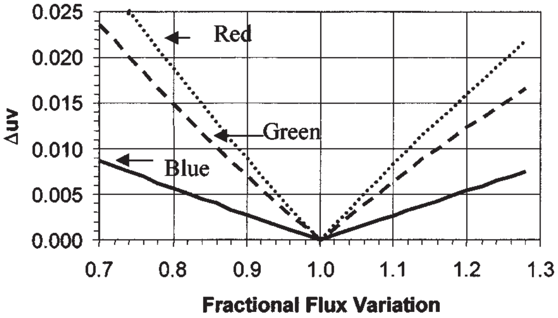

Fig. 2. The calculated shift in the (u, v) color coordinates as a result of a change in the flux of the red, green, or blue LEDs in an RGB-LED.

III. THE COLOR STABILITY OF RGB-LEDs

Conventional light sources (fluorescent, incandescent, etc) can be manufactured very reproducibly such that the lumen output and color points are highly consistent (a few percent in flux and a Δuv of less than 0.003). As a result, the general illumination market has grown to expect this level of consistency. The manufacturing process for LEDs, on the other hand, does not provide this level of consistency. Nominally identical LEDs can vary in light output by over a factor of two, and the wavelength can vary by many nanometers. Lumen output and wavelength also change with temperature [6] and lumen output changes over time in a way that cannot be accurately predicted. These factors all influence the color point that is obtained by mixing the light from a combination of different wavelength LEDs. We now discuss the quantitative effect of these LED characteristics based on white light from RGB-LEDs.

The largest impact on color point of RGB-LEDs comes from changes in light output of the individual LEDs. This can be as a result of aging, or from the initial spread in the performance of the LEDs used in the lamp. Fig. 2 shows a calculation of the color error that occurs if any one of the red, green, or blue components changes in intensity. At a color temperature of 3000 K, a change of less than 10% in intensity of either green or red moves the color point by $\Delta uv = 0.005$, already outside the specification of a fluorescent lamp. This is a very small intensity change

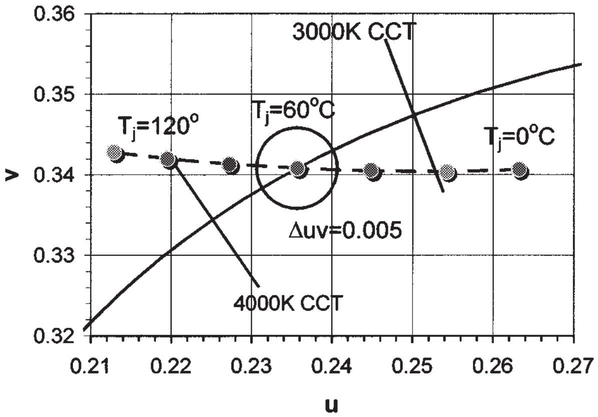

Fig. 3. The calculated shift in (u, v) coordinates of an RGB-LED as the temperature is changed in increments of 20 °C. The RGB-LED has a color temperature of 3 500 K for a junction temperature of 60 °C.

compared with the variability in nominally identical LEDs. Relative changes over lifetime between the different LEDs can be far greater than 10%.

Change in temperature of the LED pn junction leads to changes in light output, wavelength and spectral width. These all influence the resulting color point of the RGB-LED. This is illustrated in Fig. 3, which shows the calculated change in color point on the (u, v) plane as the temperature changes in increments of 20 °C. The system is set to be on the black body locus at a junction temperature of 60 °C, with a color temperature of 3500 K. The calculation is based on typical temperature coefficients of the LEDs. A shift in temperature of only 10 °C moves the color point by $\Delta uv = 0.005$. The largest contribution to this shift is the reduction of light output of the red LED as the temperature increases. As a result, the color point moves toward the blue-green. The red LEDs (or any AlInGaP-based LED), typically reduces its light output by 10–15% for every 10 °C increase in temperature. If it were possible to reduce the temperature sensitivity of the red LEDs, the stability of white light from RGB-LEDs with temperature could be significantly improved.

In addition to the effects already discussed, the peak wavelength of an LED also shifts with current. Thus, as the intensity of RGB-LEDs is adjusted by changing the amplitude of the drive current to each of the LEDs, the color point of the combination will change. While this effect limits the accuracy of the color point, it is typically less critical than the effects shown in Figs. 2 and 3.

Changes in light output and peak wavelength with temperature, and changes in light output over time mean that factory calibrations will not be sufficient to produce a stable white light RGB-LED product. The large variability in the performance parameters of LEDs makes compensation schemes based on temperature measurement and time inadequate. The problem can be solved with appropriate feedback schemes used to control the color point. We now discuss how this can be done, and the performance those feedback schemes can achieve.

IV. FEEDBACK SCHEMES

There are several measurable quantities that can be used for compensation and feedback control schemes using thermal, electrical, or optical sensors. The output of these sensors is fed to a feedback controller, which adjusts the current to the red, green, and blue LEDs to produce the desired white light output. In this section, we describe a number of different approaches to feedback control: temperature feed-forward compensation, flux feedback, combined temperature and flux control, and feedback of the color coordinates of the white light.

A. Temperature Feed Forward Compensation

The simplest measurement to implement is temperature. It is not practical to directly measure the junction temperature of the LED, and therefore, the temperature of the heatsink on which the LEDs are mounted is measured. Thus, only an indirect measure of the junction temperature is made. As discussed above, the light flux and wavelength of an LED both vary with temperature. If the color point is correct at an initial set temperature, then the white color point can be maintained as the temperature changes provided that the temperature dependence of the flux and wavelength of each color LED is known. At each temperature the required fluxes of the red, green, and blue LEDs must be calculated based on the calculated wavelengths for that temperature. The currents required to produce that flux must also be calculated for each color LED. A problem with this method of compensation is that the temperature dependence of the flux and wavelength are not precisely known. These LED parameters have a significant distribution just as the efficiency and wavelength do (see Section III). This introduces significant errors in the resulting white color point. An additional problem with this simple compensation scheme isthat it does not correct for changes in LED flux with time. Given the variability in the aging characteristics of LEDs, adding a simple correction based on hours of operation would not adequately address the issue.

B. Feedback Control of the LED Flux

Photodiodes can be used to measure the LED flux of each color component directly. The feedback controller simply has to maintain the preset flux from each color component to roughly maintain the white point. This can be done with a set of three photodiodes, each photodiode placed to detect only a single color component. It is also possible to use pulsing techniques such that only a single photodiode is needed to monitor each of the three color components. Feedback control of the fluxes of each of the color components will correct for the LED aging and the variation of LED flux with temperature. This provides improved white light control compared to that obtained with temperature feed forward alone, and does correct for the aging of the LEDs. The disadvantage of this approach is that it does not correct for the shift in wavelength with temperature. Calculation shows that temperature changes of 20 °C can result in a color point shift Δuv of more than 0.005.

C. Combined Temperature and Flux Feedback

An improved feedback control system can be achieved by combining both temperature feed forward and flux feedback. This has all the advantages of the flux feedback discussed above, and uses the temperature feed forward to allow corrections to be made for the shift in wavelength with temperature. This scheme

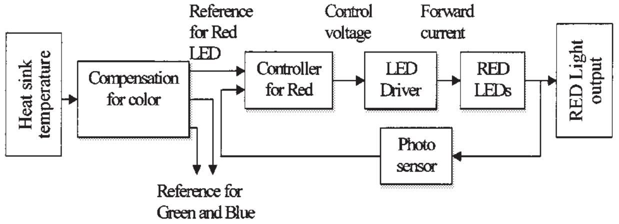

Fig. 4. Block diagram of a control system with temperature feed forward and LED light output feedback.

still relies on knowing the temperature dependence of wavelength on temperature, and thus suffers from the spread in LED characteristics. Fig. 4 shows a block diagram of such a control system. The compensation system supplies reference red, green, and blue light outputs as a function of temperature to three independent single-input-single-output (SISO) feedback controllers, which regulate the RGB-LED light outputs to the reference values.

D. *Feedback of the Color Coordinates*

Direct control of the white light from RGB-LEDs can be achieved by measuring the color coordinates of the white light. The measurement requires sensors with spectral responses matching the CIE 1931 color matching functions. The feedback signal then gives the (X, Y, Z) color coordinates. The sensors would consist of three photodiodes each covered with an appropriate optical filter. A properly designed controller then directly regulates the white light to the target color point. A high degree of color accuracy is possible with this scheme. However, there can be errors in sensing the tristimulus values due to inaccuracies in the color filters used. This tristimulus feedback control overcomes the variability in LED performance since it directly controls the white light, and not the components that go to make up the white light. Such feedback schemes, therefore, have the potential to be more accurate than the control methods described above.

Either pulsewidth modulation (PWM) or amplitude modulation (AM) can be used to supply the LED forward current with the feedback schemes presented above. However, PWM and AM driving conditions affect the spectral response of the LEDs differently. A change in the amplitude of the drive current of an LED causes a shift in its wavelength, as described above. Control methods that do not measure the color coordinates directly must take account of this if AM drive schemes are used. In the case of PWM driving of the LEDs, the current does not affect the wavelength of the LED as the dc forward current is always at the same value.

V. AN EXPERIMENTAL CONTROL SYSTEM

We have carried out experimental verification of the operation of a feedback control system for RGB-LEDs with temperature feed forward and flux feedback. We now describe the experimental setup and present the results obtained.

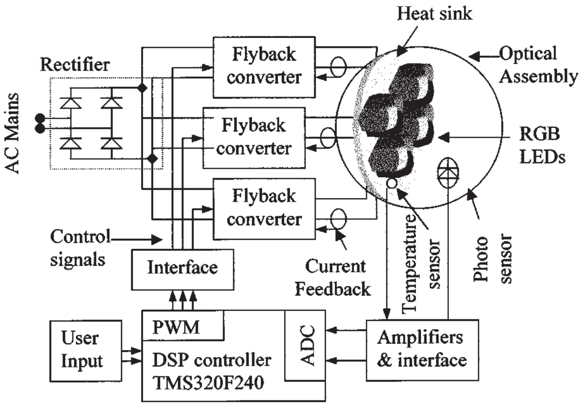

Fig. 5. Schematic of an RGB-LED lamp with feedback control system.

Fig. 5 shows a schematic of an RGB-LED white light source with this type of feedback control. The white light source is constructed from four red LEDs, eight green LEDs, and four blue LEDs. The LEDs are mounted on a heat sink using thermally conducting epoxy. A single temperature sensor (LM35 from National Semiconductors) is used to measure the temperature of the heat sink. The heatsink has a heater on it so that the temperature can be varied. A single Si photodiode (VTB113 from EG&G) is used to measure the light output from the red, green, and blue LEDs. The LEDs and the photodiode are mounted inside an integrating sphere to provide ideal mixing of the light from the different wavelength LEDs, to ensure that the photodiode sees all the LEDs equally, and to shield the experiment from ambient light. The integrating sphere is connected to a spectral lamp measurement system (spectrometer) to measure the chromaticity coordinates of the mixed white light. This is used to measure the performance of the feedback system. In an actual illumination system, the integrating sphere would be replaced by color mixing optics suited to the application.

Three independent flyback converters operating at a constant switching frequency of 100-kHz drive the RGB-LED light source. We used a PWM driving scheme operating at a frequency of 120 Hz for these experiments. Each flyback converter contains a current loop to maintain a constant peak current for the PWM pulses. In order to minimize the rise time and the fall time for the PWM current pulses, a small value of output filter capacitance is used. In addition, an inductor in series with the LEDs is used to reduce the current ripple. The color control system (shown in Fig. 4) is implemented in a DSP TMS320F240, which supplies the PWM turn-on and turn-off signals for the power supply.

The photodiode measures the flux of each of the three LED wavelengths according to the scheme shown in Fig. 6. In this example, it is assumed that the duty ratio for green is largest, and for blue is smallest. The rise and fall times for the current pulses are assumed to be negligible. In Fig. 6, the start of the PWM current pulse for red is aligned at the start of the overall PWM period, the pulse for green is centered in the period, and the end of the pulse for blue is aligned at the end of the period. Although many other configurations are possible, the pulse positioning shown in Fig. 6 provides a complete measurement in a single PWM period. The light measurements are taken in a predefined sequence of four points during the PWM cycle. The individual flux components of the red, green, and blue LEDs are obtained by differential measurements as follows: Each photodiode measurement provides the flux from one or more colors plus any ambient light. Subtracting the fluxes at two of the measurement

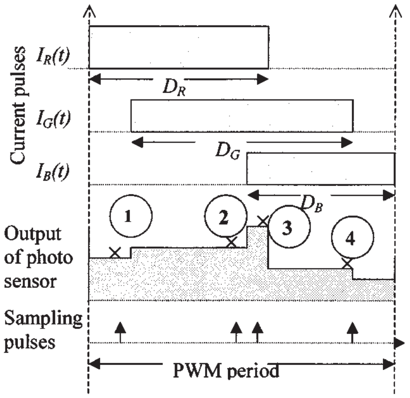

Fig. 6. Light measurement using a single photosensor with the elimination of ambient light.

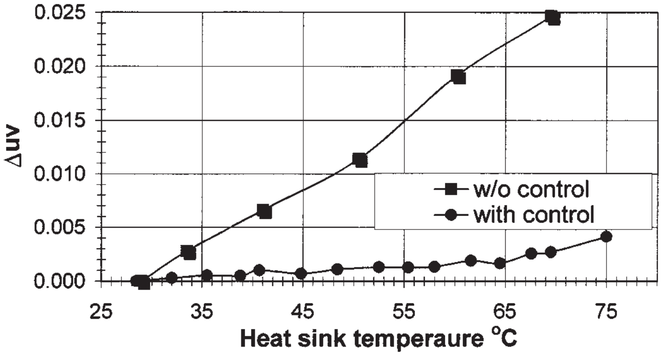

Fig. 7. The measured color error as a function of heat sink temperature of an RGB-LED lamp both open loop, and with a control system using temperature feed forward and flux feedback.

points gives the LED fluxes with the ambient light component eliminated. The red, green, and blue fluxes are given by the difference between measurements three and four, two and one, and three and two, respectively.

The experimental setup as described was used to examine the performance of this type of feedback scheme. The system was initially calibrated at a fixed temperature by adjusting the relative drive currents of the red, green, and blue LEDs until the spectrometer showed that the desired color point had been achieved. The white point was then monitored with the spectrometer as the temperature of the heatsink was slowly increased. The experimentally measured color shift for an open loop system is shown in Fig. 7. The result shows a color shift Δuv of about 0.005 for a temperature change of 10 °C, comparable to the predicted shift shown in Fig. 3. Fig. 7 also shows the performance of the feedback control system with variation in temperature. The color point only changes by $\Delta uv = 0.004$ with a temperature change of 50 °C. The change in lumen output over the same temperature change was found to be less than 3%. These results show that this type of control system can be used to produce a stable white light source from RGB-LEDs.

VI. STATISTICAL ANALYSIS OF PRODUCT YIELD

The experimental results discussed above have demonstrated the ability of the feedback system to maintain a precalibrated white point. However, what happens if no calibration is performed, and the set of LEDs is picked out of the production distribution at random? A statistical model has been developed to study this issue.

An LED light source is constructed from six red, six green, and six blue LEDs. Each LED is characterized by a number of parameters including flux (lumens per amp), wavelength, spectral width, forward voltage (V_f), and temperature coefficients of flux and wavelength. The values of these parameters are assigned at random based on a Gaussian distribution that approximates typical distributions of each parameter achieved in production. The LED spectrum is modeled as a second-order Lorentzian. All these parameters are based on a junction temperature of 25 °C. The LED junction temperature at a given heatsink temperature is calculated from the power dissipation (the product of current and V_f), and the thermal conductivity from the chip to the heatsink. We assume ideal optical mixing such that the white light output is a combination of all 18 LEDs in the lamp. The required drive currents for the red, green and blue LEDs to generate white light can be calculated based on the nominal performance of the LEDs (i.e., the mean of the Gaussian distributions for each of the LED performance parameters).

Once the LED performance parameters are selected, the actual color point of the lamp can be calculated. This can be compared with the designed color point, and a color error (Δuv) calculated. The color error will be dependent on the actual performance parameters selected, and those over a large number of LED lamps will have a statistical distribution. We typically calculate the color error for 5 000–10 000 lamps to determine this distribution. From the distribution of color errors, the product yield for a maximum acceptable color error can be calculated. The model can also calculate the effect of compensation and feedback schemes on the white light performance. The steady state function of a given control system is also included in the simulation together with a model for the sensors and LED drivers. The effect of AM or PWM driving scheme can also be modeled.

A number of different control schemes have been modeled, providing the product yield as a function of color accuracy. The modeling results for three different control schemes are shown in Fig. 8. The simplest control scheme involves only temperature feed-forward compensation (see Section IV). The simulation results show that less than 20% of products will have a color error of less than 0.005. It is clear that this control scheme will not achieve the performance required for illumination applications. If the control scheme is extended to include flux feedback of the red, green, and blue components (see Section V), a much improved product yield is achieved. As shown in Fig. 8, over 80% of products will have a color error of less than .005, and 100% yield is achieved with a color error of 0.01. We also show the result of a more complex feedback scheme that uses a wavelength feed-forward compensation scheme in addition to flux feedback. Color filters together with photodiodes are used to sense the wavelength shifts from the nominal value. This approach can further improve product yield, giving 98% yield for a color error of only 0.005.

The results of our simulations show that it is possible to design feedback control systems for RGB-LEDs that are capable of producing the required color accuracy for illumination ap-

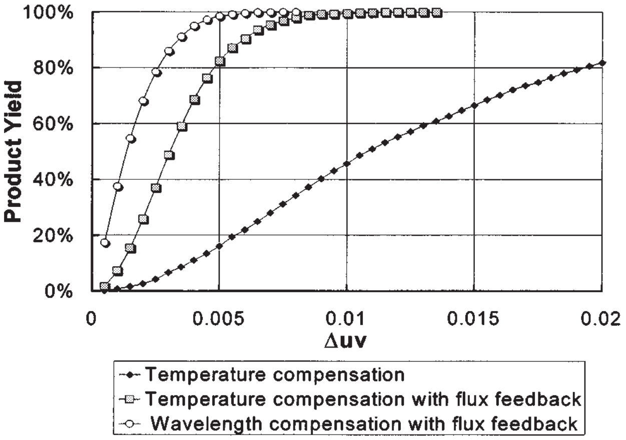

Fig. 8. The calculated product yield as a function of maximum color error for three different feedback control systems.

plications despite the large variability in LED characteristics. In the results presented in Fig. 8 we have assumed that each of the control measurements (temperature, flux, etc) are without errors. In practice, there will be some errors in the feedback signals themselves arising from the characteristics and variability of the feedback sensors. These inaccuracies can also be modeled, and their effect on product yield determined. We find that it is important to keep such measurement errors to only a few percent. The performance of feedback control schemes can be improved with the addition of some limited factory calibrations. This can take the form of a measurement on the finished lamp, or by preselecting a smaller range of performance characteristics for the LEDs used to construct the lamp.

VII. SUMMARY

We have shown both experimentally and theoretically that practical white light sources can be produced from a combination of red, green, and blue LEDs. The requirements of the illumination market for color accuracy are very stringent. Typically, the white point must be accurate to better than $\Delta uv = 0.005$. Due to the variability in LED performance parameters, and the dependence of flux and wavelength on temperature, it is not possible to achieve the required color accuracy without an electronic control system. A feedback control system using temperature feed-forward compensation and flux feedback achieves the required level of color control and a relatively high product yield of over 80% for typical variation in LED characteristics. Further improvements can be made to the feedback scheme to give very high product yields of over 95%. Such control systems will enable lighting systems to be developed that bring new illumination features to the market. RGB-LED light sources will provide variable color sources, such that the user can select the desired color point as well as the desired intensity from a single lamp.

The success of this type of light source in the general illumination market will depend on efficacy and cost. The rapid improvement in LED efficiencies indicate that within the next few years, LED white light sources will be available that can meet the efficacy of current compact fluorescent lamps. The challenge ahead is to reduce the cost of the LED lamp, including the LED chips and feedback control system.

REFERENCES

[1] M. G. Craford, "LED's challenge the incandescents," *IEEE Circuits and Devices Mag.*, vol. 8, pp. 24–29, Sept. 1992.

[2] ——, "Visible light emitting diode technology: High performance, more colors, and moving into incandescent lamp applications," in *Quantum Electronics and Laser Science Conf.*, 1996, pp. 28–28.

[3] R. Haitz, "Another semiconductor revolution: This time it's lighting," in *Proc. Ninth International Symposium on the Science & Technology of Light Sources*, 2001, pp. 319–328.

[4] C. Holen and G. Harbers, "LCD backlighting with high luminescent colored light emitting diodes," in *Proc. Ninth International Symposium on the Science & Technology of Light Sources*, 2001, pp. 373–374.

[5] G. Wyszecki and W. S. Stiles, *Color Science*. New York: Wiley, 1982.

[6] A. Bergh, G. Craford, A. Duggal, and R. Haitz, "The promise and challenge of solid-state lighting," *Physics Today*, pp. 42–47, Dec. 2001.

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US 20030230765A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2003/0230765 A1**

Dry (43) **Pub. Date: Dec. 18, 2003**

(54) **LIGHT EMITTING DIODE LIGHT SOURCE**

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(73) Assignee: **OPTOLUM, INC.**, Scottsdale, AZ

(21) Appl. No.: **10/430,698**

(22) Filed: **May 5, 2003**

Related U.S. Application Data

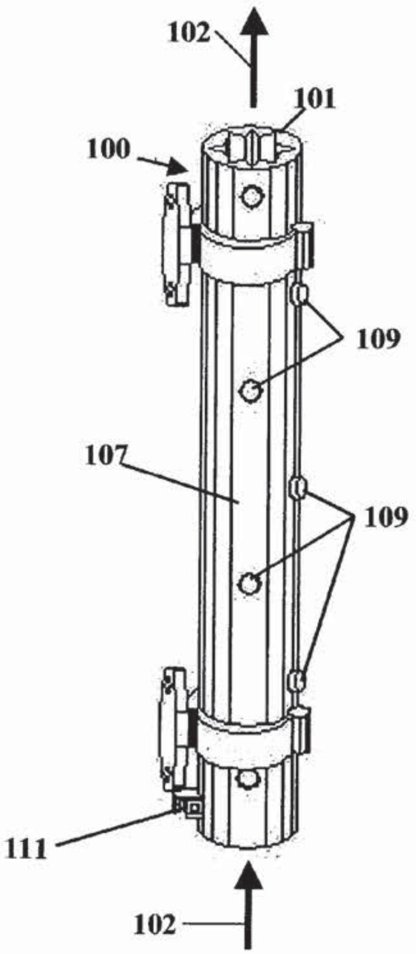
(63) Continuation-in-part of application No. 10/156,810, filed on May 29, 2002, now Pat. No. 6,573,536.

Publication Classification

(51) **Int. Cl.**^{7} **H01L 31/0328**
(52) **U.S. Cl.** **257/200**

(57) **ABSTRACT**

A light source that utilizes light emitting diodes that emit white light is disclosed. The diodes are mounted on an elongate member having at least two surfaces upon which the light emitting diodes are mounted. The elongate member is thermally conductive and is utilized to cool the light emitting diodes. In the illustrative embodiment, the elongate member is a tubular member through which a heat transfer medium flows. A cooling or fluid movement device coupled with the elongate thermally conductive member enhances cooling of the light emitting diodes.



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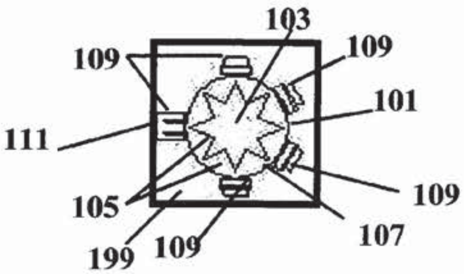

FIG. 2

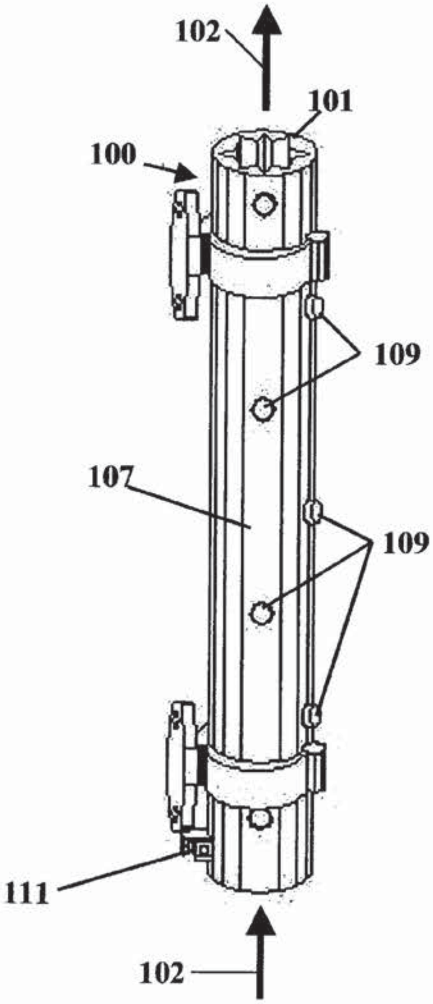

FIG. 3

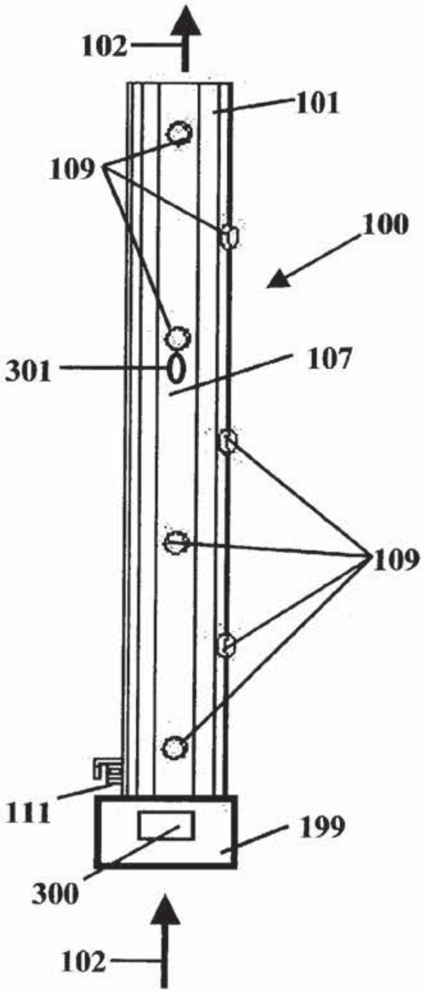

FIG. 1

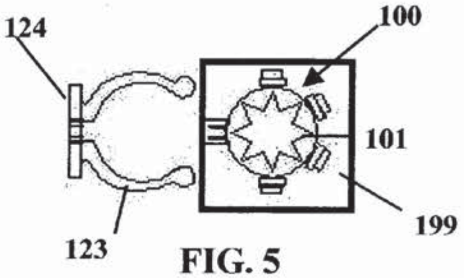

FIG. 5

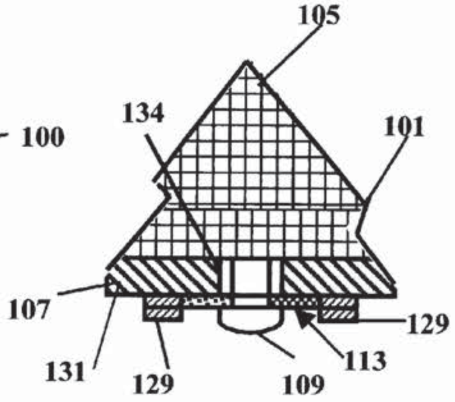

FIG. 6

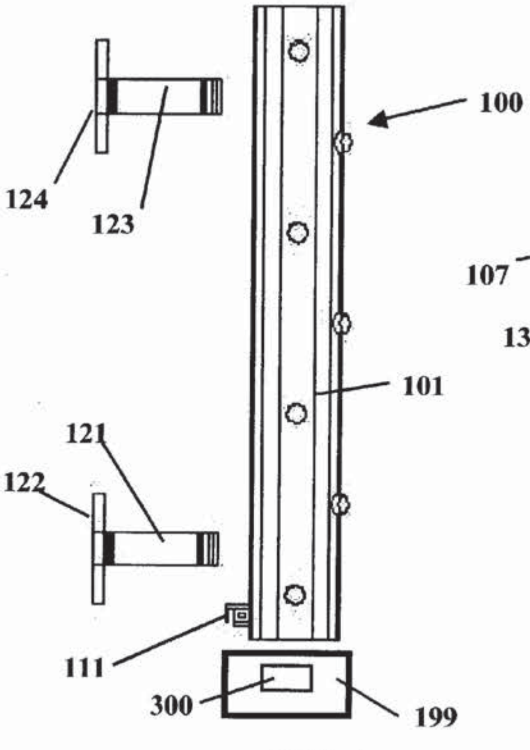

FIG. 4

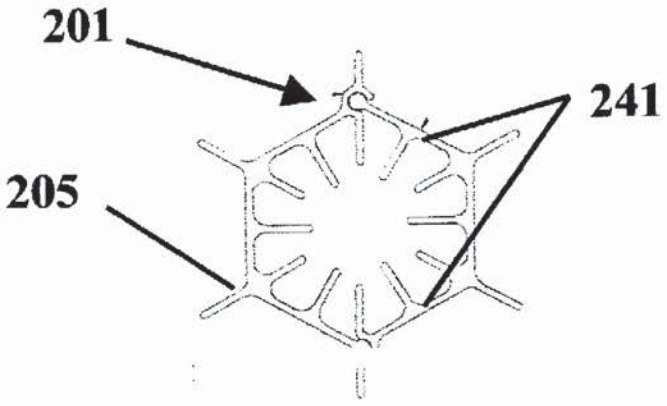

FIG. 7

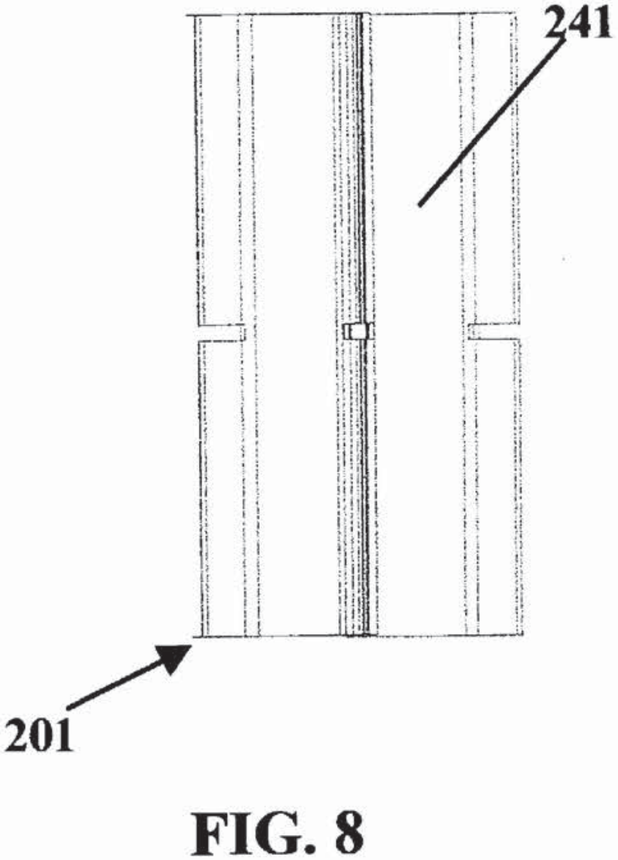

FIG. 8

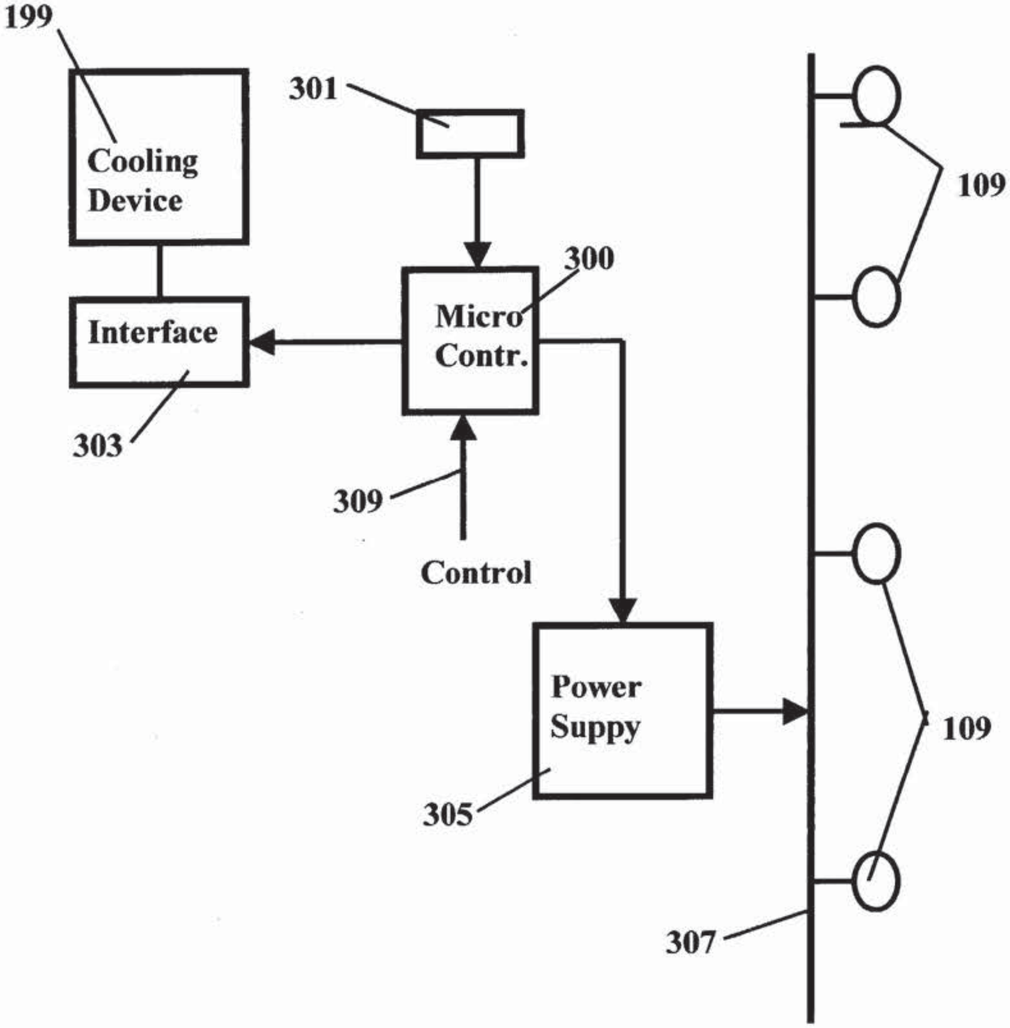
199
Cooling Device
301
109
300
Interface
Micro Contr.
303
309
Control
Power Suppy
109
305
307

FIG. 9

LIGHT EMITTING DIODE LIGHT SOURCE

RELATED APPLICATIONS

[0001] This application is a continuation-in-part of my co-pending application Ser. No. 10/156,810 filed May 29, 2002.

FIELD OF THE INVENTION

[0002] This invention pertains to lighting sources, in general, and to a lighting source that utilizes Light Emitting Diodes (LED's), in particular

BACKGROUND OF THE INVENTION

[0003] LED's have many advantages as light sources. However, in the past LED's have found application only as specialized light sources such as for vehicle brake lights, and other vehicle related lighting, and recently as flashlights. In these prior applications, the LED's are typically mounted in a planar fashion in a single plane that is disposed so as to be perpendicular to the viewing area. Typically the LED planar array is not used to provide illumination, but to provide signaling.

[0004] Recent attempts to provide LED light sources as sources of illumination have been few, and generally unsatisfactory from a general lighting standpoint.

[0005] It is highly desirable to provide a light source utilizing LED's that provides sufficient light output so as to be used as a general lighting source rather than as a signaling source.

[0006] One problem that has limited the use of LED's to specialty signaling and limited general illumination sources is that LED's typically generate significant amounts of heat. The heat is such that unless the heat is dissipated, the LED internal temperature will rise causing degradation or destruction of the LED.

[0007] It is therefore further desirable to provide an LED light source that efficiently conducts heat away from the LED's.

SUMMARY OF THE INVENTION

[0008] In accordance with the principles of the invention, an improved light source is provided. The light source includes an elongate thermally conductive member having an outer surface. A plurality of light emitting diodes is carried on the elongate member outer surface. At least some of the light emitting diodes are disposed in a first plane and others of said light emitting diodes are disposed in a second plane not coextensive with the first plane. Electrical conductors are carried by the elongate thermally conductive member and are connected to the plurality of light emitting diodes to supply electrical power thereto. The elongate thermally conductive member conducts heat away from the light emitting diodes to a thermally conductive fluid medium. A cooling device is utilized to remove heat from the light emitting diodes. In one aspect of the invention, the cooling device comprises a fluid moving device utilized to cause the fluid medium to flow to cause cooling of the elongate thermally conductive member and therefore to dissipate heat from the light emitting diodes. In another aspect of the invention, the cooling device may be an electronic or solid state device such as a Piezoelectric device or a device that uses the Peltier effect, known as a Peltier device.

[0009] In accordance with the principles of the invention, a temperature sensor is provided to determine the temperature of the light emitting diodes. The temperature sensor is coupled to a controller that monitors the temperature and controls the cooling device to vary the degree of cooling in accordance with the monitored temperature. In addition, the controller can be used to control the power provided to the light emitting diodes in response to the monitored temperature. Still further, the controller may be operated to control the light output provided by the light emitting diodes.

[0010] In the illustrative embodiment of the invention, the fluid medium is air and the fluid moving device is an air moving device.

[0011] In accordance with one aspect of the invention, an illustrative embodiment of the invention utilizes light emitting diodes that emit white light. However, other embodiments of the invention may utilize light emitting diodes that are of different colors to produce monochromatic light or the colors may be chosen to produce white light or other colors.

[0012] In accordance with another aspect of the invention the elongate thermally conductive member transfers heat from the light emitting diodes to a medium within said elongate thermally conductive member. In the illustrative embodiment of the invention, the medium is air.

[0013] In accordance with another aspect of the invention, the elongate thermally conductive member has one or more projections or fins to enhance heat transfer to the medium. The projections or fins may be disposed on the outer surface or inner surface of the elongate thermally conductive member or may be disposed on both the outer and inner surfaces.

[0014] In accordance with another aspect of the invention the elongate thermally conductive member comprises a tube. In one embodiment of the invention, the tube has a cross-section in the shape of a polygon. In another embodiment of the invention, the tube has a cross-section having flat portions.

[0015] In accordance with another embodiment of the invention, the elongate thermally conductive member comprises a channel.

[0016] In accordance with the principles of the invention, the elongate thermally conductive member may comprise an extrusion, and the extrusion can be highly thermally conductive material such as aluminum.

[0017] In one preferred embodiment of the invention the elongate thermally conductive member is a tubular member. The tubular member has a polygon cross-section. However, other embodiments my have a tubular member of triangular cross-section.

[0018] In one embodiment of the invention, a flexible circuit is carried on a surface of said elongate thermally conductive member; the flexible circuit includes the electrical conductors.

[0019] In another aspect of the invention, the flexible circuit comprises a plurality of apertures for receiving said plurality of light emitting diodes. Each of the light emitting diodes is disposed in a corresponding one of the apertures and affixed in thermally conductive contact with said elongate thermally conductive member.

[**0020**] The elongate thermally conductive member includes a thermal transfer media disposed therein in a flow channel.

[**0021**] At least one clip for mounting the elongate thermally conductive member in a fixture may be included.

BRIEF DESCRIPTION OF THE DRAWING

[**0022**] The invention will be better understood from a reading of the following detailed description of a preferred embodiment of the invention taken in conjunction with the drawing figures, in which like reference indications identify like elements, and in which:

[**0023**] **FIG. 1** is a planar side view of a light source in accordance with the principles of the invention,

[**0024**] **FIG. 2** is a top planar view of the light source of **FIG. 1**;

[**0025**] **FIG. 3** is a perspective view of the light source of **FIG. 1** with mounting clips;

[**0026**] **FIG. 4** is a planar side view of the light source of **FIG. 3** showing mounting clips separated from the light source;

[**0027**] **FIG. 5** is a top view of the light source and mounting clips of **FIG. 4**;

[**0028**] **FIG. 6** is a partial cross-section of the light source of **FIG. 1**;

[**0029**] **FIG. 7** is a top view of an alternate elongate thermally conductive member,

[**0030**] **FIG. 8** is a side view of the member of **FIG. 7**; and

[**0031**] **FIG. 9** is a block diagram of a control arrangement for the light source of the invention.

DETAILED DESCRIPTION

[**0032**] A light source in accordance with the principles of the invention may be used as a decorative lighting element or may be utilized as a general illumination device. As shown in **FIG. 1, a** light source **100** in accordance with the invention includes an elongate thermally conductive member or heat sink **101**. Elongate heat sink **101** is formed of a material that provides excellent thermal conductivity. Elongate heat sink **101** in the illustrative embodiment of the invention is a tubular aluminum extrusion. To improve the heat dissipative properties of light source **100**, elongate heat sink **101** is configured to provide convective heat dissipation and cooling. As more clearly seen in **FIG. 2**, tubular heat sink **101** is hollow and has an interior cavity **103** that includes one or more surface discontinuities or heat dissipating protrusions **105**. In the illustrative embodiment the surface discontinuities or heat dissipating protrusions **105** are triangular shaped fins, but may take on other shapes. In yet other embodiments, the surface discontinuities may include apertures or blind bores either alone or in combinations with heat dissipation protrusions. Protrusions **105** are integrally formed on the interior of elongate heat sink **101**. In the illustrative embodiment movement of a medium **102** through elongate heat sink **101** provides cooling. Medium **102** utilized in the illustrative embodiment is air, but may in some applications be a fluid other than air to provide for greater heat dissipation and cooling.

[**0033**] Cooling device **199** is coupled to elongate thermally conductive member **101** to enhance cooling of the LED's. Cooling device in one embodiment of the invention is a medium moving device in fluid coupling with elongate thermally conductive member **101** to enhance the movement of medium **102**. Medium moving device **199** is utilized to enhance fluid medium **102** to flow to cause cooling of the elongate thermally conductive member and therefore to dissipate heat from the light emitting diodes. Medium moving device **199** in a first illustrative embodiment is a fan and may be an electromechanical fan, electronic fan, or solid-state device such as a piezoelectric fan. In a second embodiment of the invention, cooling device **199** may comprise one or more solid state cooling devices utilizing the Peltier effect, otherwise known as Peltier devices. Although cooling device **199** is shown at one end of the light source **100**, it will be appreciated by those skilled in the art that where solid state devices are utilized, a plurality of solid state devices may be positioned at locations other than on an end of the light source **100**. It will also be appreciated by those skilled in the art that solid state cooling devices such as Piezoelectric and Peltier devices are known.

[**0034**] A controller **300** is provided in accordance with the principles of the invention. Controller **300** is coupled to a temperature sensor **301** that is disposed on light source **100** so as to monitor the temperature of the light emitting diodes **109**. Controller **300** is utilized to control the rate of cooling provided by cooling device **199**. It will be appreciated by those skilled in the art that although controller **300** and sensor **301** are shown separated from each other in the drawing, that such separation is provided merely for clarity in understanding the invention and controller **300** and sensor **301** may be fabricated as a single integrated device.

[**0035**] The exterior surface **107** of elongate heat sink **101** has a plurality of Light Emitting Diodes **109** disposed thereon. Each LED **109** in the illustrative embodiment comprises a white light emitting LED of a type that provides a high light output. Each LED **109** also generates significant amount of heat that must be dissipated to avoid thermal destruction of the LED. As noted above cooling device **199** provides cooling to avoid thermal destruction. By combining a plurality of LEDs **109** on elongate thermally conductive member or heat sink **101**, a high light output light source that may be used for general lighting is provided.

[**0036**] Conductive paths **129** are provided to connect LEDs **109** to an electrical connector **111**. The conductive paths may be disposed on an electrically insulating layer **131** or layers disposed on exterior surface **107**. In the illustrative embodiment shown in the drawing figures, the conductive paths and insulating layer are provided by means of one or more flexible printed circuits **113** that are permanently disposed on surface **107**. As more easily seen in **FIG. 6**, printed circuit **113** includes an electrically insulating layer **131** that carries conductive paths **129**. As will be appreciated by those skilled in the art, other means of providing the electrically conductive paths may be provided.

[**0037**] Flexible printed circuit **113** has LED's **109** mounted to it in a variety of orientations ranging from 360 degrees to 180 degrees and possibly others depending on the application. Electrical connector **111** is disposed at one end of printed circuit **113**. Connector **113** is coupleable to a separate power supply to receive electrical current. Flexible printed circuit **113**, in the illustrative embodiment is coated with a non-electrically conductive epoxy that may be infused with optically reflective materials. Flexible printed circuit **113** is adhered to the tube **101** with a heat conducting epoxy to aid in the transmission of the heat from LEDs **109** to tube **101**. Flexible printed circuit **113** has mounting holes **134** for receiving LEDs **109** such that the backs of LEDs **109** are in thermal contact with the tube surface **107**.

[**0038**] Tubular heat sink **101** in the illustrative embodiment is formed in the shape of a polygon and may have any number of sides. Although tubular heat sink **101** in the illustrative embodiment is extruded aluminum, tubular heat sink **101**may comprise other thermal conductive material. Fins **105** may vary in number and location depending on particular LED layouts and wattage In some instances, surface discontinuities such as heat dissipation protrusions or fins may be added to the exterior surface of tubular heat sink **101**. In addition, apertures may be added as surface discontinuities to the tubular heat sink to enhance heat flow.

[**0039**] **FIGS. 7 and 8** show an alternate elongate thermally conductive member **201** that has both exterior surface discontinuities or heat dissipation protrusions or fins **205** in addition to interior surface discontinuities or heat dissipation protrusions or fins **241**.

[**0040**] Turning now to **FIG. 9**, controller **300** is advantageously utilized in accordance with the principles of the invention. Controller **300** may be any one of a number of commercially available controllers. Each such controller is programmable and includes a processor, and memory (which are not shown). Controller **300** memory is utilized to program operation of the microprocessor. It will be appreciated by those skilled in the art that controller **300** may be integrated into the same chip as sensor **301** and interface **303** that is utilized to interface controller **300** to the cooling device **199**. Controller **300** is programmed so that when temperature sensor **301** detects a temperature that is too high, cooling device **199** is activated or, if activated at less than full capacity, is activated to a higher cooling capacity. In addition, controller **300** is coupled to power supply **305**, which in turn provides power to LED's **109** at the appropriate voltage level and type via power bus **307**, so that the amount of power provided to LED's **109** may also be regulated to control the amount of power dissipated by LED's **109**. Controller **300** controls the amount of cooling provided by cooling device **199**. The amount of cooling provided by cooling device **199** is increased when temperature sensor **301** indicates a predetermined temperature. In addition, controller **300** will turn off all LED's **109** in the event that a second predetermined temperature threshold is reached or exceeded. Controller **300** also operates to increase the power provided to LED's **109** in the event that the temperature sensed is below another predetermined threshold. Controller **300** has control input **309** to receive control inputs to determine the on-off status of LED's **109** and to determine the brightness level output of LED's **109**. In addition, controller **300** is programmed to be

[**0041**] responsive to control signals that will command controller **300** to brighten or dim the light output of LED's **109** Interface **303** is provides the appropriate interface between controller **300** and cooling device **199**

[**0042**] Light source **100** is mounted into a fixture and retained in position by mounting clips **121,123** as most clearly seen in **FIGS. 3, 4**, and **5** Each of the clips is shaped so as to engage and retain light source **100**. Each clip is affixed on one surface **122, 124** to a light fixture.

[**0043**] Although light source **100** is shown as comprising elongate tubular thermally conductive members or heat sinks **101, 201**, other extruded elongate members may be used such as channels.

[**0044**] In the illustrative embodiment shown, cooling by flow of air through elongate thermally conductive members or tubular heat sinks **101, 201** is utilized such that cool or unheated air enters elongate thermally conductive members **101, 201** by fluid movement device **199**, passes over the surface discontinuities or heat dissipation protrusions, and exits from the opposite end of elongate thermally conductive member **101, 201** as heated air. In higher wattage light sources, rather than utilizing air as the cooling medium, other fluids may be utilized. In particular, convective heat pumping may be used to remove heat from the interior of the heat sink.

[**0045**] In one particularly advantageous embodiment of the invention, the light source of the invention is configured to replace compact fluorescent lighting in decorative applications.

[**0046**] It will be appreciated by those skilled in the art that although the invention has been described in terms of light emitting diodes, the invention is equally applicable to other non-filament miniature lights sources such as organic light emitting diodes (OLED's) and polymer type light sources. It is intended that the term "light emitting diode" or "LED" as used in the claims is intended to not be limited to solid state light emitting diodes, but is intended to include such other miniature light sources.

[**0047**] It has further been determined that the uniformity of light distribution of a light source having an elongate thermally conductive member with heat dissipation protrusions or fins **205** on the outer surface of the elongate thermally conductive member **201** is enhanced by utilization of an appropriately selected coating or treatment to the outer or exterior surfaces of elongate thermally conductive member **201**. In particular, in a comparison of various surface coatings or treatments, it has been found that the use of a non-reflective or black surface on the protrusions or fins **205** provides a more uniform light output. It has been determined that the use of reflective or white surfaces on protrusions results in the protrusions producing shadows in the light output.

[**0048**] As will be appreciated by those skilled in the art, the principles of the invention are not limited to the use of light emitting diodes that emit white light. Different colored light emitting diodes may be used to produce monochromatic light or to produce light that is the combination of different colors.

[**0049**] Controller **300** is programmable to be further responsive to control signals **309** to control which of different colored LED's are activated and the amount of power provided to the different colors such that the color output of lights source **100** is varied.

[0050] Although the invention has been described in terms of illustrative embodiments, it is not intended that the invention be limited to the illustrative embodiments shown and described. It will be apparent to those skilled in the art that various changes and modifications may be made to the embodiments shown and described without departing from the spirit or scope of the invention. It is intended that the invention be limited only by the claims appended hereto.

What is claimed is:

1. A light source comprising:

an elongate thermally conductive member having an outer surface;

a plurality of light emitting diodes (LED's) carried on said elongate member outer surface at least some of said light emitting diodes being disposed in a first plane and others of said light emitting diodes being disposed in a second plane not coextensive with said first plane;

said elongate thermally conductive member being configured to conduct heat away from said light emitting diodes to fluid contained by said elongate thermally conductive member;

temperature sensing apparatus providing signals representative of the temperature of said light emitting diodes; and

a controller coupled to said LED's and to said temperature sensing apparatus for controlling the temperature of said LED's dependent upon predetermined temperatures.

2. A light source in accordance with claim 1, comprising:

a cooling device coupled to said elongate thermally conductive member to enhance cooling of said LED's, said fluid cooling device being controllable by said controller.

3. A light source in accordance with claim 2, wherein:

said cooling device comprises an electromechanical device.

4. A light source in accordance with claim 3, wherein:

said electromechanical device comprises a fan.

5. A light source in accordance with claim 2, wherein:

said cooling device comprises an electronic device.

6. A light source in accordance with claim 2, wherein:

said cooling device comprises a solid state device.

7. A light source in accordance with claim 2, wherein:

said cooling device comprises an piezoelectric device.

8. A light source in accordance with claim 1, wherein:

said elongate thermally conductive member is configured to conduct heat away from said light emitting diodes to fluid proximate said elongate member outer surface.

9. A light source in accordance with claim 7, wherein:

said fluid proximate said elongate member outer surface comprises air.

10. A light source in accordance with claim 2, wherein:

said cooling device comprises a fan.

11. A light source in accordance with claim 2, wherein:

said cooling device comprises a Peltier device.

12. A light source in accordance with claim 1, wherein:

said controller controls the amount of power provided to each of said LED's.

13. A light source in accordance with claim 12, wherein:

said controller determines the amount of power provided to each of said LED's based upon control signal inputs.

14. A light source in accordance with claim 13, wherein:

said controller determines the amount of power provided to each of said LED's in dependence upon signals received from said temperature sensor.

15. A light source in accordance with claim 1, wherein:

at least some of said light emitting diodes emit colored light.

16. A light source in accordance with claim 15, wherein:

said controller controls each of said light emitting diodes to control the color of the light output of said light source.

17. A light source comprising:

an elongate thermally conductive member having an outer surface,

at least one light emitting diode carried on said elongate member outer surface;

said elongate thermally conductive member being configured to conduct heat away from said at least one light emitting diode;

a cooling apparatus coupled to said elongate thermally conductive member to enhance cooling of said at least one light emitting diode; and

a controller for controlling operation of said cooling apparatus.

18. A light source in accordance with claim 17, wherein:

said controller controls power provided to said at least one light emitting diode.

19. A light source in accordance with claim 17 wherein:

said cooling device comprises a Peltier device

20. A light source in accordance with claim 17 wherein:

said cooling device comprises a Piezoelectric device.

* * * * *

US 20100259182A1

(19) **United States**

(12) **Patent Application Publication**

MAN et al.

(10) **Pub. No.: US 2010/0259182 A1**

(43) **Pub. Date: Oct. 14, 2010**

(54) **LIGHT SOURCE INTENSITY CONTROL SYSTEM AND METHOD**

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(21) Appl. No.: **12/161,812**

(22) PCT Filed: **Feb. 9, 2007**

(86) PCT No.: **PCT/CA07/00188**

§ 371 (c)(1),
(2), (4) Date: **Jul. 23, 2008**

Related U.S. Application Data

(60) Provisional application No. 60/772,458, filed on Feb. 10, 2006, provisional application No. 60/830,196, filed on Jul. 11, 2006.

(30) **Foreign Application Priority Data**

Jul. 18, 2006 (CA) 2552685

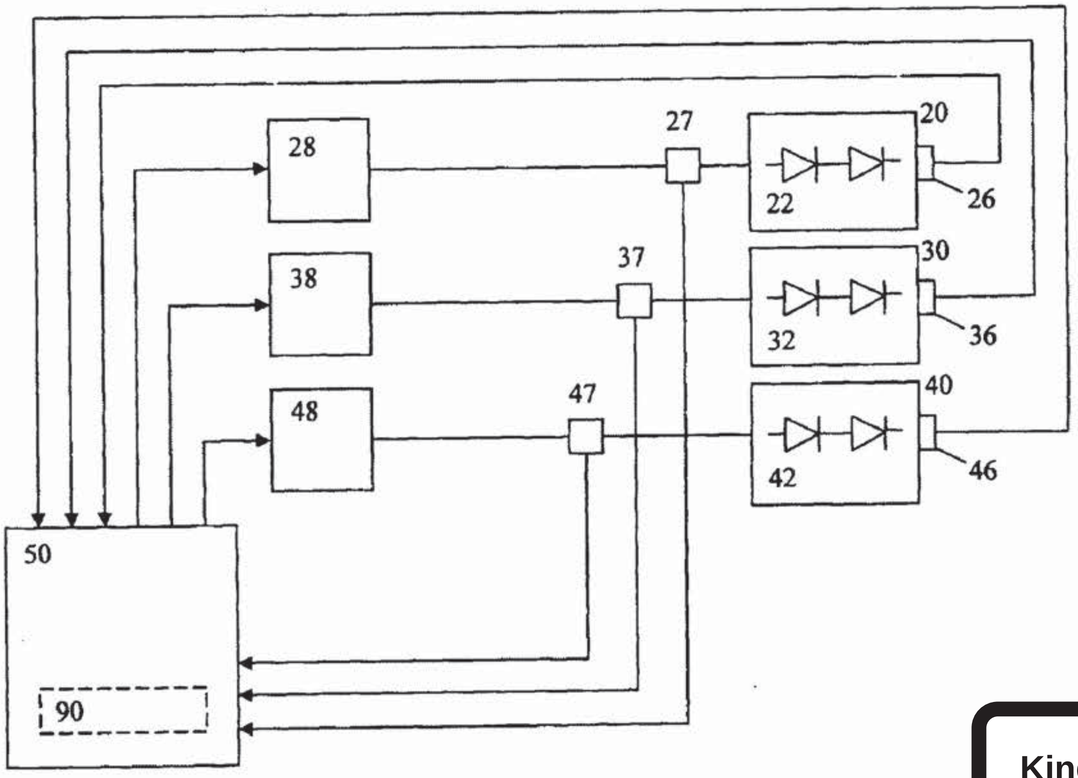
Publication Classification

(51) **Int. Cl.**
H05B 37/02 (2006.01)

(52) **U.S. Cl.** **315/250**; 315/297

(57) **ABSTRACT**

The light source comprises one or more first light-emitting elements for generating light having a first wavelength range and one or more second light-emitting elements for generating light having a second wavelength range. The first light-emitting elements and second light-emitting elements are responsive to separate control signals provided thereto. A control system receives a signal representative of the operating temperature from one or more sensing devices and determines first and second control signals based on the desired colour of light and the operating temperature. The light emitted by the first and second light-emitting elements as a result of the received first and second control signals can be blended to substantially obtain the desired colour of light. The desired colour of light generated can thus be substantially independent of junction temperature induced changes in the operating characteristics of the light-emitting elements.



King Exhibit
1053 (8-8-23)
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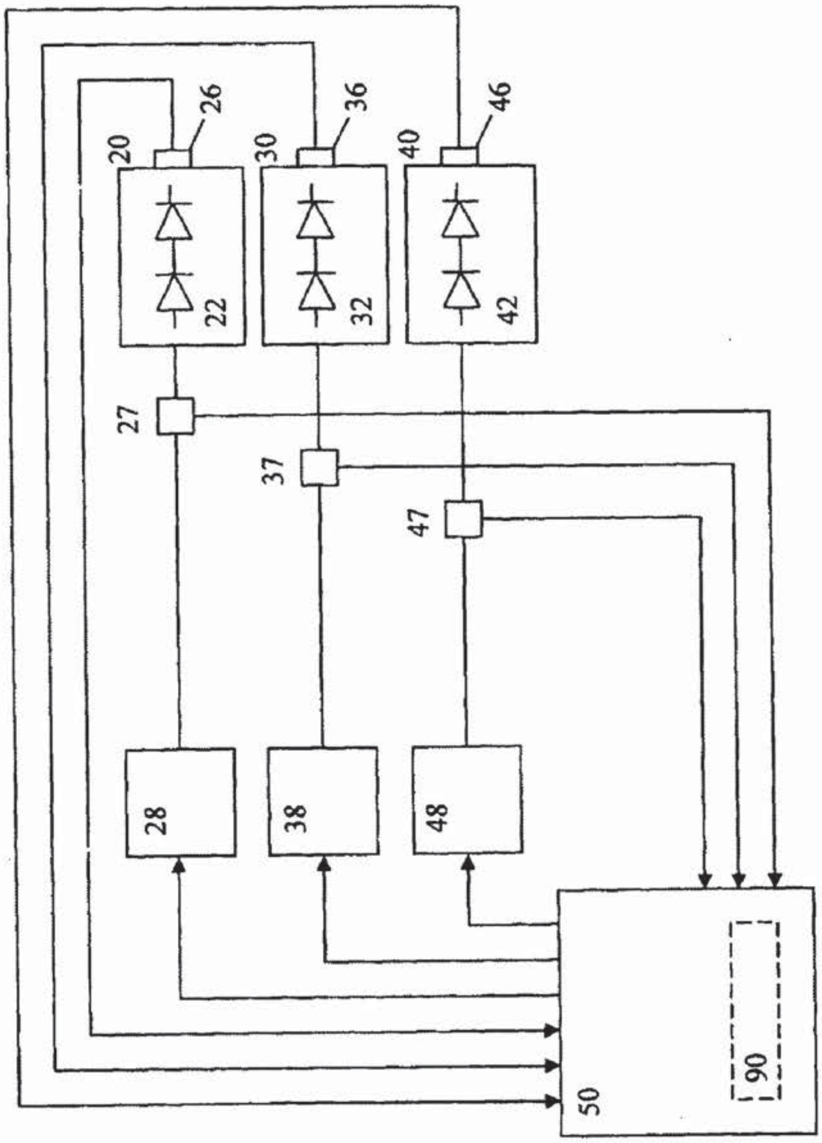
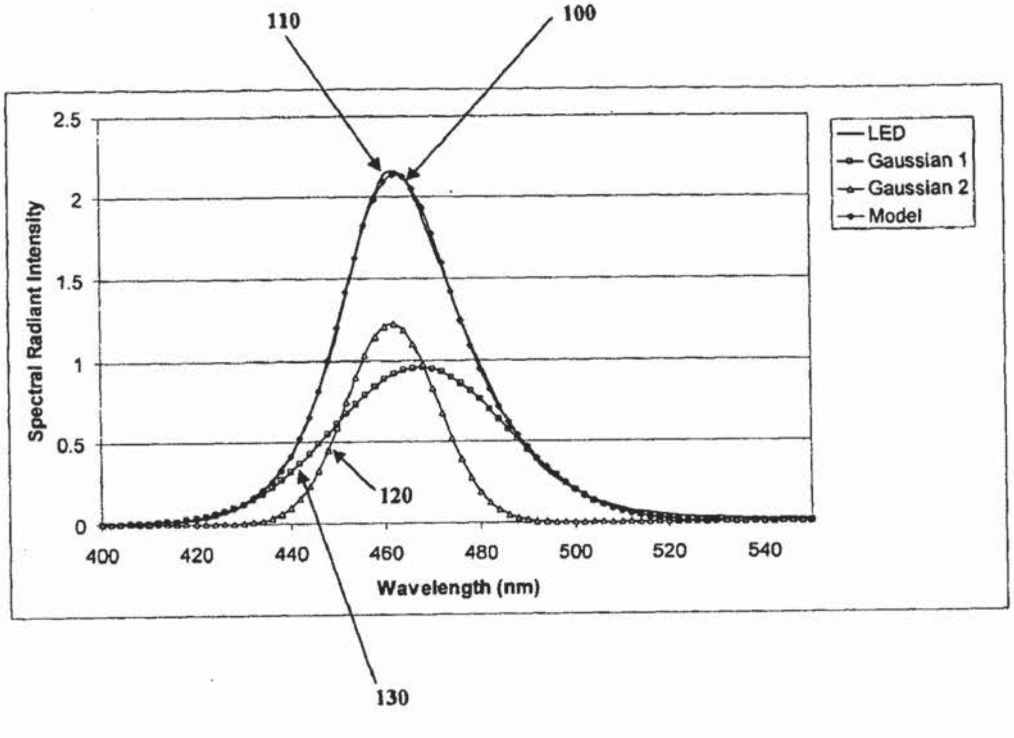


FIGURE 1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2
1.5
1
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Spectral Radiant Intensity
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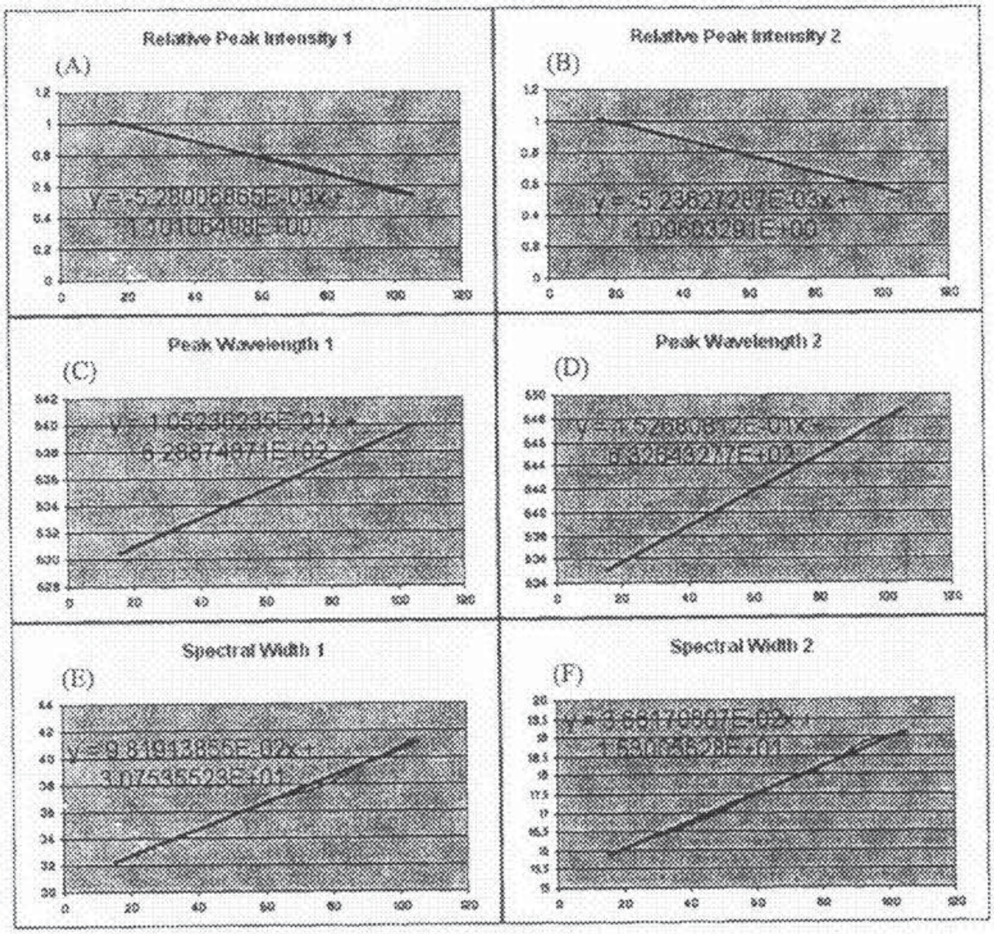
420
440
460
480
500
520
540
Wavelength (nm)
LED
Gaussian 1
Gaussian 2
Model
120
130

FIGURE 2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1.2
0
20
40
60
80
100
120
Relative Peak Intensity 2
(B)
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0
0.2
0.4
0.6
0.8
1
1.2
0
20
40
60
80
100
120
Peak Wavelength 1
(C)
y = 1.05238235E-01x + 6.28874871E+02
628
630
632
634
636
638
640
642
0
20
40
60
80
100
120
Peak Wavelength 2
(D)
y = 1.52880852E-01x + 6.32543277E+02
634
636
638
640
642
644
646
648
650
0
20
40
60
80
100
120
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(E)
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36
38
40
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44
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40
60
80
100
120
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(F)
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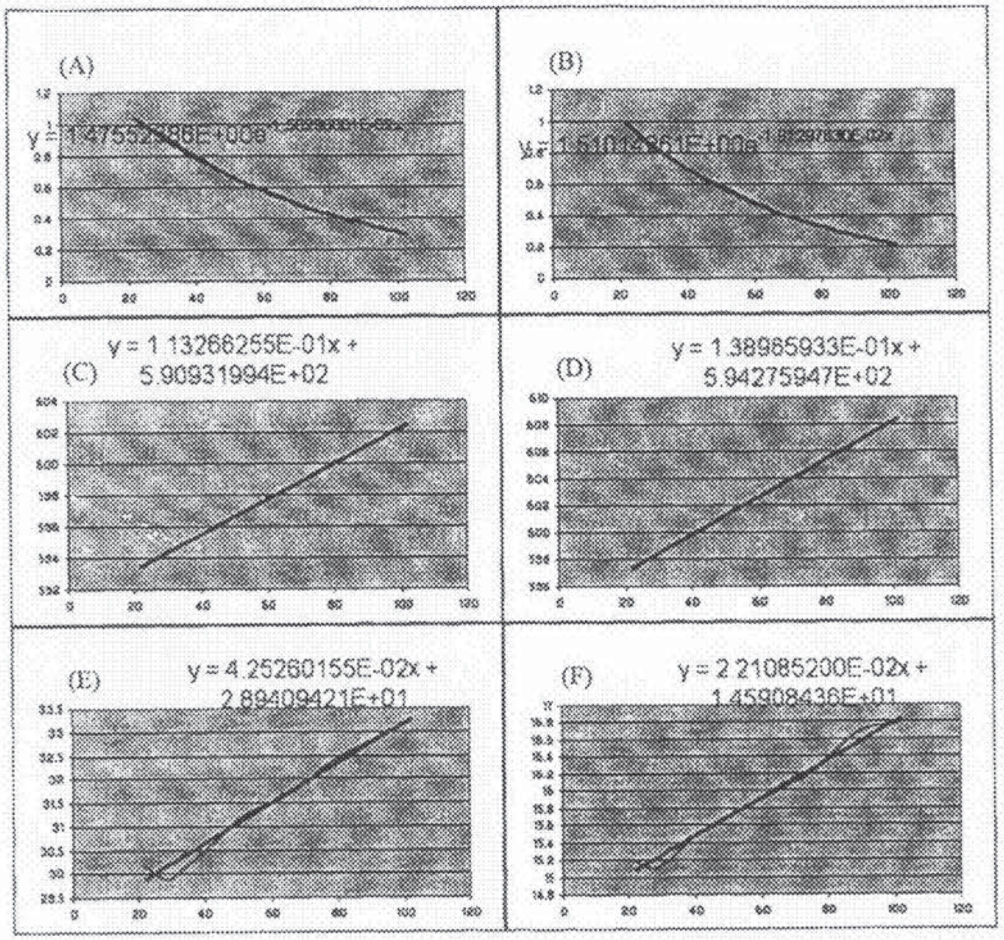
40
60
80
100
120

FIGURE 3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80
100
120
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0.6
0.4
0.2
0
0
20
40
60
80
100
120
(C)
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5.90931994E+02
604
602
600
598
596
594
592
0
20
40
60
80
100
120
(D)
y = 1.38965933E-01x +
5.94275947E+02
610
608
606
604
602
600
598
596
0
20
40
60
80
100
120
(E)
y = 4.25260155E-02x +
2.89409421E+01
33.5
33
32.5
32
31.5
31
30.5
30
29.5
0
20
40
60
80
100
120
(F)
y = 2.21085200E-02x +
1.45908436E+01
17
16.8
16.6
16.4
16.2
16
15.8
15.6
15.4
15.2
15
14.8
0
20
40
60
80
100
120

FIGURE 4

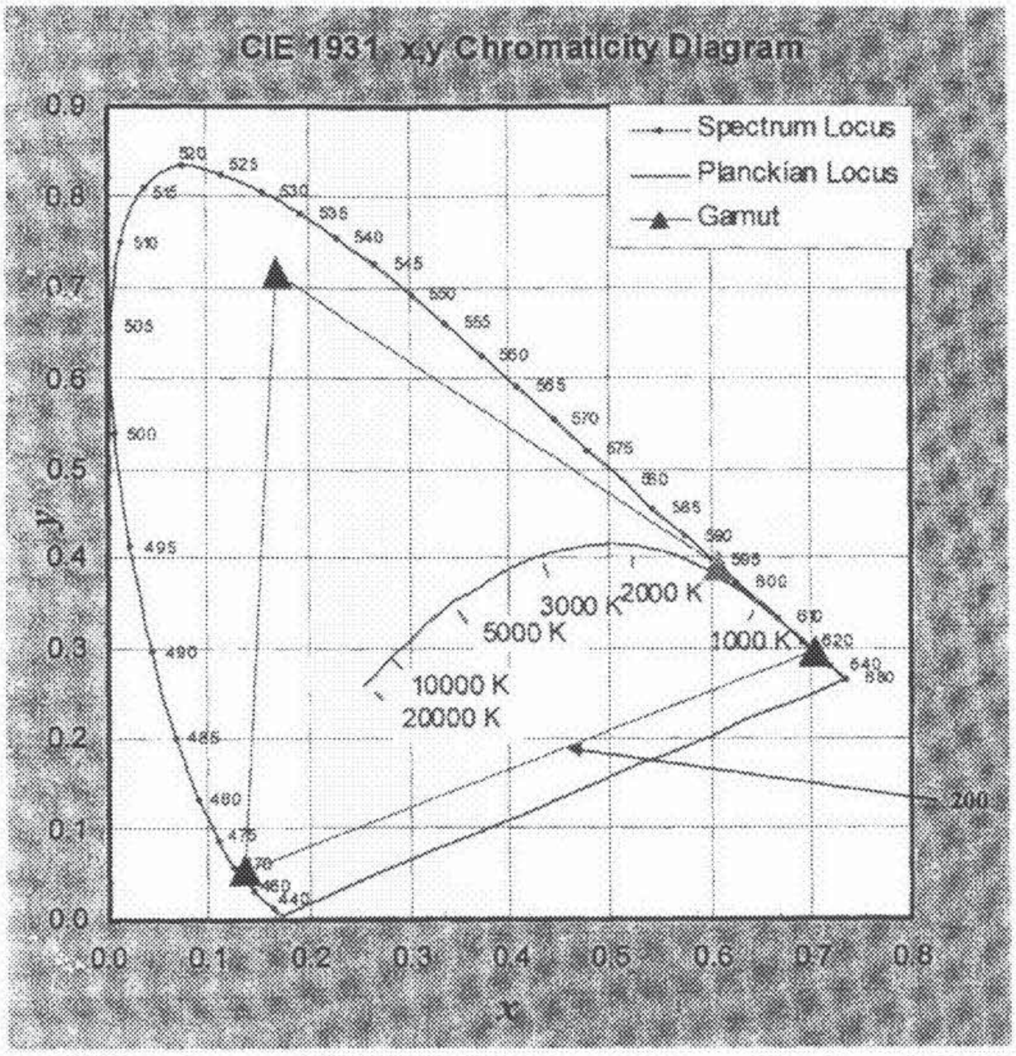
CIE 1931 x,y Chromaticity Diagram
Spectrum Locus
Planckian Locus
Gamut
520
525
530
535
540
545
550
555
560
565
570
575
580
585
590
595
600
610
620
640
680
515
510
505
500
495
490
485
480
475
470
460
440
3000 K
2000 K
5000 K
1000 K
10000 K
20000 K
200
y
x
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

FIGURE 5

LIGHT SOURCE INTENSITY CONTROL SYSTEM AND METHOD

FIELD OF THE INVENTION

[0001] The present invention pertains to the field of illumination and in particular to an intensity control system for a light source.

BACKGROUND

[0002] Recent advances in the development of semiconductor light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs) have made these devices suitable for use in general illumination applications, including architectural, entertainment, and roadway lighting, for example. As such, these devices are becoming increasingly competitive with light sources such as incandescent, fluorescent, and high-intensity discharge lamps.

[0003] Due to its natural lighting characteristics, white light is typically the preferred choice for lighting. An important consideration for LED-based luminaires used for ambient lighting and LED-based backlighting for liquid crystal displays (LCDs) is the need to produce natural white light. White light can be generated by mixing the light emitted from different colour LEDs.

[0004] Various standards have been proposed to characterize the spectral content of light. One way to characterize light emitted by a test light source is to compare it with the light radiated by a black body and identify the temperature of the black body at which its perceived colour best matches the perceived colour of the test light source. That temperature is called correlated colour temperature (CCT) and is usually measured in Kelvin (K). The higher the CCT, the bluer, or cooler the light appears. The lower the CCT, the redder, or warmer the light appears. An incandescent light bulb has a CCT of about 2856 K, and fluorescent lamps can have CCTs in the range of about 3200K to 6500 K.

[0005] Furthermore the properties of light can be characterized in terms of luminous flux and chromaticity. Luminous flux is used to define the measurable amount of light and chromaticity used to define the perceived colour impression of light, irrespective of its perceived brightness. Chromaticity and luminous flux are measured in units according to standards of the Commission Internationale de l'Eclairage (CIE). The CIE chromaticity standards define hue and saturation of light based on chromaticity coordinates that specify a position in a chromaticity diagram. The chromaticity coordinates of light are derived from tristimulus values and expressed by the ratio of the tristimulus values to their sum; i.e. $x=X/(X+Y+Z)$, $y=Y/(X+Y+Z)$, $z=Z/(X+Y+Z)$, where x, y and z are the chromaticity coordinates and X, Y, and Z are the tristimulus values. Because $x+y+z=1$, it is only necessary to specify two chromaticity coordinates such as x and y, for example. Any CCT value can be transformed into corresponding chromaticity coordinates.

[0006] In spite of their success, LED-based light sources can be affected by a number of parameters in a complex way. Chromaticity and luminous flux output of LEDs can greatly depend on junction temperature, which can have undesirable effects on the CCT and more generally the chromaticity of the emitted light.

[0007] Ignoring temperature dependencies, the amount of light emitted by an LED is proportional to its instantaneous forward current. If the LEDs are pulsed at a rate greater than about 60 Hz, the human visual system perceives a time-averaged amount of light as opposed to individual pulses. As a result, light source dimming can be achieved by varying the amount of time-averaged forward current, using such techniques as pulse width modulation (PWM) or pulse code modulation (PCM). However, changes in the average forward current can affect the junction temperature of the LED, which can alter the spectral power distribution and in consequence the CCT or chromaticity and luminous flux of the light emitted by the LED. The compensation of this effect can become complex when various coloured LEDs are used to generate mixed light of a desired chromaticity. As discussed by M. Dyble, in "Impact of Dimming White LEDs: Chromaticity Shifts Due to Different Dimming Methods," Fifth International Conference on Solid State Lighting, Bellingham, Wash.; SPIE Vol. 5941, 2005, colour appearance of the resultant mixed light can shift unacceptably when dimming, as the spectral power distribution of the individual LEDs can change.

[0008] LED junction temperature variations can also cause undesired effects in the spectral power distribution of the resultant output light. Variations in junction temperature not only can reduce the luminous flux output, but can also cause undesirable variations in the CCT of the mixed light. Furthermore, overheating of LEDs can also reduce the life span of LEDs.

[0009] In order to overcome these limitations, various methods for generating natural white light have been proposed. U.S. Pat. No. 6,448,550 to Nishimura teaches a solid-state illumination device having a plurality of LEDs of different colours and use optical feedback. Light from the LEDs is measured by photosensitive sensors mounted in close proximity with LEDs and compared with a reference set of responses to a previously measured spectral power distribution. The amount of variation between the sensor responses to the light from the LEDs and the previously measured spectral power distribution is used as a basis for adjusting the current to the LEDs in order to maintain the light from the LEDs as close as possible to the pre-determined spectral power distribution. While the Nishimura reference provides a way to achieve control of the spectral power distribution of the output light with a desired colour property, it uses a complex optical feedback system.

[0010] U.S. Pat. No. 6,507,159 to Muthu discloses a control method and system for an LED-based luminaire having a plurality of red, green and blue light LEDs for generating a desired light by colour mixing. Muthu seeks to alleviate the unwanted variations in the luminous flux output and CCT of the desired light by providing a control system with a feedback system including filtered photodiodes, a mathematical transformation for determining tristimulus values of the LEDs, and a reference-tracking controller for resolving the difference between the feedback tristimulus values and the desired reference tristimulus values in order to adjust the forward current of the LEDs, such that the difference in tristimulus values is reduced to zero. The calculations as required by Muthu for the mathematical transformations can, however, make it difficult to implement an optical feedback control system with a response time that is fast enough to avoid visual flicker during dimming operations, for example.

[0011] U.S. Pat. No. 6,576,881 to Muthu et al. discloses a method and system for controlling the output light generated by red, green, and blue LEDs. Sensors positioned proximate to the LEDs to detect a first set of approximate tristimulus values of the output light. The first set of tristimulus values is communicated to a controller, which converts these values into a second set of tristimulus values representative of a standard colourimetric system. The relative luminous flux output of the LEDs is adjusted on the basis of the difference between the second set of the tristimulus values and a set of user-specified tristimulus values. Based on this configuration, as with some previously identified prior art, the calculations required for the mathematical transformations can make it difficult to implement an optical feedback control system with a response time that is fast enough to avoid visual flicker during dimming operations, for example.

[0012] U.S. Pat. No. 6,630,801 to Schuurmans provides a method and system for sensing the colour point of resultant light produced by mixing coloured light from a plurality of LEDs in the RGB colours. The system comprises a feedback unit for generating feedback values corresponding to the chromaticity of the resultant light based on values obtained from filtered and unfiltered photodiodes that are responsive to the light from the LEDs. The system also comprises a controller which adjusts the resultant light based upon the difference between the feedback values and values representative of the chromaticity of a desired resultant light. While the Schuurmans reference provides a way to achieve control of the spectral power distribution of the output light with a desired colour property, it also uses a complex optical feedback system.

[0013] U.S. Patent Publication No. 2003/0230991 to Muthu et al. discloses an LED-based white-light backlighting system for electronic displays. The backlighting system of Muthu et al. includes a plurality of LEDs of different light colours arranged such that the combination of light colours produces white light. The system also comprises a microprocessor which monitors the luminous flux, radiant flux, or tristimulus levels of the white light and controls the luminous flux and chromaticity of the white light by feedback control. The backlighting system of Muthu et al. uses photodiodes with filters to determine approximate tristimulus values of the LEDs and adjusts the luminous flux and chromaticity of the white light. While the Muthu et al. reference provides a way to achieve control of the spectral power distribution of the output light with a desired colour property, it uses a complex optical feedback system.

[0014] U.S. Pat. No. 6,441,558 also to Muthu et al. discloses a multi-colour LED-based luminaire for generating light at different colour temperatures. The desired luminous flux output for each array of colour LEDs is achieved by using a controller system that adjusts the current supplied to the LEDs based on the chromaticity of the desired light and the junction temperature of the LEDs. One of the shortcomings associated with the LED-based luminaire of Muthu et al. is that in order to measure the luminous flux of an array of LEDs, an optical feedback sensor is used to obtain the luminous flux from the LEDs which is communicated to the controller by a polling sequence. According to Muthu et al., the measurement sequence begins by measuring the luminous flux output of the all LED arrays in operation. Each array of LEDs is alternately switched "OFF" briefly, and a further measurement is taken. The difference between the initial measurement and the next measurement provides the light output from the LED array that was turned OFF. The measurement of the light output is repeated for the remaining LED arrays. Again, while the Muthu et al. reference provides a way to achieve control of the spectral power distribution of the output light with a desired colour property, it uses a complex optical feedback system. In addition, a drawback of this procedure as disclosed by Muthu et al. is the excessive amount of thermal stress imposed on the LEDs during ON and OFF cycles at low frequencies which are required for the optical feedback system.

[0015] Therefore, there is a need for a relatively simple light source intensity control system and method that can account for device junction temperature effects on the light emitted by the light source.

[0016] This background information is provided to reveal information believed by the applicant to be of possible relevance to the present invention. No admission is necessarily intended, nor should be construed, that any of the preceding information constitutes prior art against the present invention.

SUMMARY OF THE INVENTION

[0017] An object of the present invention is to provide a light source intensity control system and method. In accordance with an aspect of the present invention, there is provided a light source for generating a desired colour of light, said light source comprising: one or more first light-emitting elements for generating first light having a first wavelength range, the one or more first light-emitting elements responsive to a first control signal; one or more second light-emitting elements for generating second light having a second wavelength range, the one or more second light-emitting elements responsive to a second control signal; one or more sensing devices for generating one or more signals representative of operating temperatures of the one or more first light-emitting elements and the one or more second light-emitting elements; and a control system operatively coupled to the one or more first light-emitting elements, the one or more second light-emitting elements and the one or more sensing devices, the control system configured to receive the one or more signals and configured to determine the first control signal and the second control signal based upon the operating temperatures and the desired colour of light; wherein the first light and the second light are blended to create the desired colour of light.

[0018] In accordance with another aspect of the present invention there is provided a method for generating a desired colour of light, the method comprising the steps of: determining a first operating temperature of one or more first light-emitting elements which provide first light having a first spectrum; determining a second operating temperature of one or more second light-emitting elements which provide second light having a second spectrum; providing a first spectral radiant intensity model indicative of effects of the first operating temperature on the first spectrum; providing a second spectral radiant intensity model indicative of effects of the second operating temperature on the second spectrum; determining a first control signal and a second control signal based upon the first spectral radiant intensity model, the second spectral radiant intensity model, the desired colour of light and the first operating temperature and second operating temperature; providing the first control signal to the one or more first light-emitting elements; providing the second control signal to the one or more second light-emitting elements; and blending the first light and the second light into mixed light having the desired colour of light.

BRIEF DESCRIPTION OF THE FIGURES

[0019] FIG. **1** illustrates a light source according to one embodiment of the present invention.

[0020] FIG. **2** illustrates both the measured spectral radiant intensity and double Gaussian modelled spectral radiant intensity of a blue light-emitting diode according to one embodiment of the present invention.

[0021] FIG. **3** illustrates the temperature dependent variations of the parameters for a double Gaussian model of the spectral radiant intensity of a red light-emitting diode according to one embodiment of the present invention.

[0022] FIG. **4** illustrates the temperature dependent variations of the parameters for a double Gaussian model of the spectral radiant intensity of an amber light-emitting diode according to one embodiment of the present invention.

[0023] FIG. **5** illustrates the colour gamut for the three coloured light-emitting elements as defined by the CIE 1931 x,y Chromaticity Diagram.

DETAILED DESCRIPTION OF THE INVENTION

Definitions

[0024] The term "light-emitting element" (LEE) is used to define any device that emits radiation in any region or combination of regions of the electromagnetic spectrum for example, the visible region, infrared and/or ultraviolet region, when activated by applying a potential difference across it or passing a current through it, for example. Therefore a light-emitting element can have monochromatic or quasi-monochromatic spectral emission characteristics. Examples of light-emitting elements include semiconductor, organic, or polymer/polymeric light-emitting diodes, blue or UV pumped phosphor coated light-emitting diodes, optically pumped nanocrystal light-emitting diodes or any other similar devices as would be readily understood by a worker skilled in the art. Furthermore, the term light-emitting element is used to define the specific device that emits the radiation, for example a LED die, and can equally be used to define a combination of the specific device that emits the radiation together with a housing or package within which the specific device or devices are placed.

[0025] The term "luminous flux" is used to define the amount of light emitted by a light source according to standards of the Commission Internationale de l'Eclairage (CIE). Where the wavelength regime of interest includes infrared and/or ultraviolet wavelengths, the term "luminous flux" is used to include radiant flux as defined by CIE standards.

[0026] The term "chromaticity" is used to define the perceived colour impression of light according to CIE standards.

[0027] The term "intensity" is used to define the measured photometric brightness of a light source according to the standards of the Commission Internationale de l'Eclairage (CIE).

[0028] The term "spectral radiant intensity" is used to define the radiant intensity of light at a given wavelength emitted by a light source according to the standards of the CIE.

[0029] The term "emission spectrum" is used to define the distribution of spectral radiant intensity of all wavelengths of visible light.

[0030] The term "controller" is used to define a computing device or microcontroller having a central processing unit (CPU) and peripheral input/output devices (such as A/D or D/A converters) to monitor parameters from peripheral devices that are operatively coupled to the controller. These input/output devices can also permit the CPU to communicate and control peripheral devices that are operatively coupled to the controller. The controller can optionally include one or more storage media collectively referred to herein as "memory". The memory can be volatile and non-volatile computer memory such as RAM, PROM, EPROM, and EEPROM, floppy disks, compact disks, optical disks, magnetic tape, or the like, wherein control programs (such as software, microcode or firmware) for monitoring or controlling the devices coupled to the controller are stored and executed by the CPU. Optionally, the controller also provides the means of converting user-specified operating conditions into control signals to control the peripheral devices coupled to the controller. The controller can receive user-specified commands by way of a user interface, for example, a keyboard, a touchpad, a touch screen, a console, a visual, acoustic input device, or other device as is well known to those skilled in this art.

[0031] As used herein, the term "about" refers to a +/−10% variation from the nominal value. It is to be understood that such a variation is always included in any given value provided herein, whether or not it is specifically identified.

[0032] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs.

[0033] The present invention provides a light source for generating a desired colour of light. The light source comprises one or more first light-emitting elements for generating light having a first wavelength range and one or more second light-emitting elements for generating light having a second wavelength range. The first light-emitting elements and second light-emitting elements are responsive to separate control signals provided thereto. The light source further includes a sensing device for sensing operating temperature or temperatures of the first and second light-emitting elements. A control system receives a signal representative of the operating temperature(s) from the sensing device and determines the first and second control signals based on the desired colour of light and the operating temperatures. The light emitted by the first and second light-emitting elements as a result of the received first and second control signals can be blended to substantially obtain the desired colour of light. In this manner, the desired colour of light generated by the light source can be substantially independent of junction temperature induced changes in the operational characteristics of the light-emitting elements.

[0034] In another embodiment, the light source can additionally comprise one or more third light-emitting element for generating light having a third wavelength range, one or more fourth light-emitting elements for generating light having a fourth wavelength, etc, as would be readily understood by a worker skilled in the art. In this embodiment, the sensing device may be configured to sense the operating temperature of the one or more third light-emitting elements, one or more fourth light-emitting elements etc, which would be received by the control system enabling subsequent determination of control signals for these third and fourth light-emitting elements.

[0035] FIG. **1** illustrates a block diagram of a light-emitting element light source according to one embodiment of the present invention. The light source includes arrays **20**, **30**, **40** each having one or more light-emitting elements that are in thermal contact with one or more heat sinks or heat extraction mechanisms (not shown). The combination of coloured light generated by each of the red light-emitting elements **22**, green light-emitting elements **32** and blue light-emitting elements **42** can generate light of a specific chromaticity, for instance white light. In one embodiment, the light source includes mixing optics (not shown) to spatially homogenize the output light generated by mixing light from the red light-emitting elements **22**, green light-emitting elements **32**, and blue light-emitting elements **42**.

[0036] Current drivers **28**, **38**, **48** are coupled to arrays **20**, **30**, **40**, respectively, and are configured to supply current to the red light-emitting elements **22**, green light-emitting elements **32**, and blue light-emitting elements **42** in arrays **20**, **30**, **40**. The current drivers **28**, **38**, **48** control the luminous flux outputs of the red light-emitting elements **22**, green light-emitting elements **32**, and blue light-emitting elements **42** by regulating the flow of current through the red light-emitting elements **22**, green light-emitting elements **32**, and blue light-emitting elements **42**. The current drivers **28**, **38**, **48** are configured to regulate the supply of current to arrays **20**, **30**, **40** interdependently so as to control the chromaticity of the combined light as described hereinafter.

[0037] A controller **50** is coupled to current drivers **28**, **38**, **48**. The controller **50** is configured to interdependently adjust the amount of average forward current by adjusting the duty factor of the current drivers **28**, **38**, **48**, thereby providing control of the luminous flux output of the red light-emitting elements **22**, green light-emitting elements **32**, and blue light-emitting elements **42**.

[0038] In one embodiment of the present invention, a temperature sensor **26**, **36** or **46** is in thermal contact with all arrays **20**, **30** and **40** and coupled to controller **50**, thereby providing a means for measuring the operating temperature of the arrays **20**, **30**, **40**. The operating temperature of the arrays **20**, **30**, **40** can be correlated to the junction temperature of red light-emitting elements **22**, green light-emitting elements **32** and blue light-emitting elements **42**. In one embodiment, each array **20**, **30** and **40** has a separate temperature sensor **26**, **36** and **46** respectively, in order to measure each array's individual operating temperature.

[0039] In one embodiment of the present invention, alternately, or in combination with one or more temperature sensors, voltage sensors **27**, **37**, **47** are coupled to the output of current drivers **28**, **38**, **48** and measure the instantaneous forward voltage of light-emitting element arrays **20**, **30**, **40**. Controller **50** is coupled to voltage sensors **27**, **37**, **47** and configured to monitor the instantaneous forward voltage of light-emitting element arrays **20**, **30**, **40**. The forward voltage of the arrays **20**, **30**, **40** can be correlated to the junction temperature of red light-emitting elements **22**, green light-emitting elements **32** and blue light-emitting elements **42**. For example, experimentally derived correlations between junction temperature and LED peak wavelength, spectral width or output power are disclosed by Chhajed, S. et al., 2005, "Influence of Junction Temperature on Chromaticity and Colour-Rendering Properties of Trichormatic White-Light Sources Based on Light-Emitting Diodes", Journal of Applied Physics 97, 054506, herein incorporated by reference.

[0040] The controller **50**, based on the detected temperatures and/or detected forward voltages can determine the junction temperature of each of the red light-emitting elements **22**, green light-emitting elements **32** and blue light-emitting elements **42** and based on a predetermined model of temperature dependence to spectral output of each of the red light-emitting elements **22**, green light-emitting elements **32** and blue light-emitting elements **42**, together with the desired colour of light to be created, the controller can determine control signals for the control of the operation of the red light-emitting elements **22**, green light-emitting elements **32** and blue light-emitting elements **42**, in order that the desired colour of light is generated by the light source.

Light-Emitting Elements

[0041] The light-emitting elements can be selected to provide a predetermined colour of light. The number, type and colour of the light-emitting elements within the light source can provide a means for achieving high luminous efficiency, a high Colour Rendering Index (CRI), and a large colour gamut. The light-emitting elements can be manufactured using either organic material, for example OLEDs or PLEDs or inorganic material, for example semiconductor LEDs or other device configurations as would be readily understood by a worker skilled in the art. The light-emitting elements can be primary light-emitting elements that can emit colours including blue, green, red or can emit another colour or colours. The light-emitting elements can optionally be secondary light-emitting elements, which convert the emission of a primary source into one or more monochromatic wavelengths or quasi-monochromatic wavelengths. Additionally, a combination of primary and/or secondary light-emitting elements can be employed. As would be readily understood by a worker skilled in the art, the one or more light-emitting elements can be mounted for example on a PCB (printed circuit board), a MCPCB (metal core PCB), a metallized ceramic substrate or a dielectrically coated metal substrate, or the like, that carries traces and connection pads. The light-emitting elements can be in unpackaged form such as in a die format or may be packaged parts such as LED packages or may be packaged with other components including for example drive circuitry, optics and control circuitry.

[0042] In one embodiment, an array of light-emitting elements having spectral outputs centred around wavelengths corresponding to the colours red, green and blue can be selected, for example. Optionally, light-emitting elements of other spectral output can additionally be incorporated into the light source, for example light-emitting elements radiating at the red, green, blue and amber wavelength regions may be configured as arrays or optionally may include one or more light-emitting elements radiating at the cyan wavelength region, or other wavelength region as would be readily understood by a worker skilled in the art. The selection of light-emitting elements can be directly related to the desired colour gamut and/or the desired maximum luminous flux and colour rendering index to be created by the lighting module.

[0043] In one embodiment, multiple light-emitting elements can be connected electrically in a plurality of configurations. For example, the light-emitting elements can be connected in series or parallel configurations or combinations of both. In one embodiment of the present invention, two or more light-emitting elements are connected in series as strings, wherein a string may comprise light-emitting elements of the same colour bin.

[0044] In another embodiment of the present invention, light-emitting elements are electrically connected in order that each individual light-emitting element can be individually controlled. For example, a string of light-emitting elements can be wired such that some light-emitting elements can be bypassed either partially, or completely to allow this individual control of each light-emitting element independent of one another.

Sensing Device

[0045] In one embodiment of the present invention, a temperature sensor is configured to measure the junction temperature of the light-emitting elements in the arrays, wherein the single temperature sensor is strategically positioned to detect the operating temperature of all colours of light-emitting elements. For example, in one embodiment, the light-emitting elements can be mounted on a common thermally conductive substrate upon which the temperature sensor is mounted.

[0046] In an alternate embodiment, separate temperature sensors can be configured to measure the temperature of each colour of light-emitting element individually. In this manner a more accurate measure of the junction temperature of each colour of light-emitting element colour can be determined. In this embodiment, a temperature sensor can be positioned proximate to the appropriate colour of light-emitting elements. The different colours of light-emitting elements can be thermally isolated from each other or may be mounted on a common substrate or heat sink.

[0047] In accordance with one embodiment of the invention, the temperature sensor can be a thermistor, thermopile, thermocouple, integrated temperature sensing circuits, a silicon based sensor or other temperature sensing device as would be known to a worker skilled in the art, that is configured to measure the temperature of the desired light-emitting element(s).

[0048] In another embodiment, the junction temperature of the light-emitting elements is calculated based on the detected forward voltage drop across the light-emitting elements. The forward voltage drop across a light-emitting element varies substantially linearly with temperature. The forward drop across a string of light-emitting elements can thus be measured and the variation in forward voltage drop can be employed to approximately determine the instantaneous junction temperature of the light-emitting element(s).

[0049] In another embodiment, the junction temperature of the light-emitting elements can be determined using both the evaluated voltage drop across the light-emitting elements and the temperature detected by one or more temperature sensors.

[0050] In one embodiment, the sampling of data detected by a temperature sensor and/or a voltage sensor can be performed at a predetermined interval, after a predetermined operating time, continuously or randomly.

[0051] In one embodiment, the sampling rate can be adjusted during operation of the light source. The adjustment of the sampling can be dependent on for example the duty cycle of operation of a light-emitting element, a particular colour of light-emitting element or an evaluated average duty factor for all or some of the light-emitting elements in the light source.

Control System

[0052] The control system receives the temperature data from the sensing device in a format dependent on the sensing device. The control system subsequently manipulates this temperature data in order to evaluate the junction temperature of the light-emitting elements. Subsequently the control system is configured to model the emission spectrum of each light-emitting element or colour of light-emitting element, as a function of temperature. In this manner temperature modified spectral output characteristics of the light-emitting elements can be determined.

[0053] The controller is further configured to evaluate control signals for transmission to the light emitting elements. These control signals are determined based on the desired colour of light to be generated by the light source and the temperature modified spectral output characteristics of the light-emitting elements in the light source.

[0054] In one embodiment of the present invention, the spectral radiant intensity, $I(\lambda)$ of a light-emitting element, for example a semiconductor light-emitting diode, can be modeled using a double Gaussian approximation defined as follows:

$$I(\lambda) = \hat{I}_1 e^{-4\ln(2)\left(\frac{\lambda-\hat{\lambda}_1}{\Delta\lambda_1}\right)^2} + \hat{I}_2 e^{-4\ln(2)\left(\frac{\lambda-\hat{\lambda}_2}{\Delta\lambda_2}\right)^2} \tag{1}$$

where $\hat{I}_1$ and $\hat{I}_2$ are peak spectral radiant intensities, $\hat{\lambda}_1$ and $\hat{\lambda}_2$ are peak spectral radiant intensity wavelengths, $\Delta\lambda_1$ and $\Delta\lambda_2$ are spectral full width half maximum (FWHM) bandwidths and λ is the wavelength.

[0055] It would be readily understood by a worker skilled in the art that one or more of the parameters of the right hand side of Equation (1) can, for practical purposes of an application of an embodiment of the present invention, depend on further operating parameters including operating temperature T or age of the light-emitting element, for example, even when this is not explicitly indicated. It is therefore understood that, for example, $\hat{I}_1$, $\hat{I}_2$, $\hat{\lambda}_2$, $\Delta\lambda_1$ and $\Delta\lambda_2$ are merely abbreviations which can always include further parametric dependencies, for example a temperature dependence which can be explicitly expressed as $\hat{I}(T)$, if such a dependency is relevant for practical purposes.

[0056] Furthermore, it would be readily understood by a worker skilled in the art that an another function other than that described in Equation (1) and possibly with other parameters, can be used to approximate, with its own accuracy, the spectral radiant intensity $I(\lambda)$ of a light-emitting element relative to the operating temperature thereof.

[0057] In one embodiment of the present invention, an example of a double Gaussian approximation of the spectral radiant intensity of a blue light-emitting diode is illustrated in FIG. **2**. In this example the modeled approximation **100**, is substantially equal to the observed spectral radiant intensity **110** of the blue light-emitting diode being tested. In this embodiment, the modeled approximation **100** is the sum of a first Gaussian function **130** and a second Gaussian function **120**. Each of the two Gaussian functions can be defined by parameters relating to relative peak spectral radiant intensity, peak spectral radiant intensity wavelength and spectral FWHM bandwidth, which correspond to the height, centre position and width of the Gaussian function, respectively.

[0058] In one embodiment, the parameters of each Gaussian function can be experimentally evaluated for its temperature dependence thereby providing a means for determining a modeled temperature-modified spectral radiant intensity for a light-emitting element. FIGS. **3** and **4** illustrate the temperature dependence of the parameters for each Gaussian function used to generate a temperature-modified model for spectral radiant intensity of a particular red light-emitting diode and a particular amber light-emitting diode, respectively. The temperature dependence of the peak spectral radiant intensities for the first Gaussian function and the second Gaussian function are illustrated in FIGS. **3**A, **4**A and FIGS. **3**B, **4**B, respectively. The temperature dependence of the peak spectral radiant intensity wavelengths for the first Gaussian function and the second Gaussian function are illustrated in FIGS. **3**C, **4**C and FIGS. **3**D, **4**D, respectively. Finally, the temperature dependence of the spectral full width half maximum bandwidths for the first Gaussian function and the second Gaussian function are illustrated in FIGS. **3**E, **4**E and FIGS. **3**F, **4**F, respectively. In one embodiment, the parameters can be defined as being either linearly dependent or exponentially dependent on junction temperature of the light-emitting element.

[0059] In one embodiment of the present invention, the emission spectrum of a light-emitting element is measured in a certain setup with a defined reference light-emitting element operating temperature, for example 25° C. junction temperature. The double Gaussian approximation can then be curve-fitted to the emission spectrum using a known, robust minimization algorithm for solving for example a least squares or a least distance error function, thereby determining the peak spectral radiant intensity at T=25° C. described as $\hat{I}_n(25)$, the peak spectral radiant intensity wavelength at T=25° C. $\lambda_n(25)$, and spectral FWHM bandwidth at T=25° C. $\Delta\lambda_n(25)$ with $n \in \{1,2\}$. In an embodiment wherein a linear approximation is practically effective, each peak intensity $\hat{I}_n$ for $n \in \{1,2\}$ at temperature T can be defined as a first order approximation in T which can be defined as follows:

$$\hat{I}_n(T)=a_nT+b_n \tag{2}$$

wherein parameters a_n and b_n can be determined experimentally by curve fitting experimental data obtained from measuring the emission spectrum over a range of different operating temperatures. For example, as is illustrated in FIG. **3**, the spectrum of some red AlInGaP light-emitting diodes, for example, can be satisfactorily approximated using a linear approximation of $\hat{I}_n$ (T) as defined in Equation (2).

[0060] In an embodiment wherein a linear approximation is practically ineffective, an exponential temperature dependency can be used and can be defined as follows:

$$\hat{I}_n(T)=c_n\exp(-d_nT) \tag{3}$$

wherein parameters c_n and d_n can be determined experimentally by curve fitting experimental data obtained from measuring the emission spectrum over a range of different operating temperatures. For example, as is illustrated in FIG. **4** the exponential approximation as defined in Equation (3) can be useful in describing $\hat{I}_n(T)$ for certain AlInGaP light-emitting diodes.

[0061] Similarly, in one embodiment of the present invention, the peak wavelength for each $n \in \{1,2\}$ at temperature T can be defined as follows:

$$\hat{\lambda}_n(T)=e_nT+f_n \tag{4}$$

wherein parameters e_n and f_n can be determined experimentally by measuring the emission spectrum over a range of temperatures and curve fitting. For example, for the red AlInGaP light-emitting diode illustrated in FIG. **3**, $\hat{\lambda}_n(T)$ can be approximated using Equation (4). In other embodiments, exponential or other non-linear approximations may be utilized to effectively describe the temperature dependence of the peak wavelength.

[0062] Similarly, in one embodiment of the present invention, the spectral FWHM for each $n \in \{1,2\}$ at temperature T can be defined as follows:

$$\Delta\lambda_n(T)=g_nT+h_n \tag{5}$$

wherein parameters g_n and h_n can be determined experimentally by measuring the emission spectrum over a range of temperatures and curve fitting. For example, for the red AlInGaP light-emitting diode illustrated in FIG. **3**, $\hat{\lambda}_n(T)$ can be approximated using Equation (5). In other embodiments, exponential or other non-linear approximations may be utilized to effectively describe the temperature dependence of the spectral FWHM.

[0063] Example empirically-derived thermal model parameters according to an embodiment of the present invention and Equations (2) and (3) respectively, as well as Equations (4) and (5) at T=25° C. reference temperature for the linear approximations are provided in Table 1 for arbitrary units (a.u.) in intensity. It is noted that f_n and h_n for $n \in \{1,2\}$ are not specified in Table 1.

TABLE 1

LED thermal model coefficients

Parameter	Red	Amber	Green	Blue
a_1 [a.u./° C.] or d_1 [1/° C.]	−0.0052	0.0155	−0.0034	−0.0048
a_2 [a.u./° C.] or d_2 [1/° C.] [a.u./° C.]	−0.0058	0.0190	−0.0048	−0.0035
b_1 or c_1 [a.u.]	1.1295	1.4747	1.0856	1.1191
b_2 or c_2 [a.u.]	1.1462	1.6066	1.1207	1.0881
e_1 [nm/° C.]	0.1107	0.1120	0.0000	0.0226
e_2 [nm/° C.]	0.1526	0.1387	0.0445	0.0504
g_1 [nm/° C.]	0.0831	0.0428	0.1051	0.1081
g_2 [nm/° C.]	0.0327	0.0209	0.0562	0.0903

[0064] In an embodiment of the present invention, the control system can be configured with a model which can adequately represent the thermal coupling, for example thermal transfer, between light-emitting elements in a light-emitting element cluster. Such a model can be used to determine, in a feed-forward manner, the mutual heating effects which can occur when light-emitting elements are mounted, for example, on a common substrate.

[0065] In one embodiment of the present invention, the heat Q dissipated by a light-emitting element is approximately equal to its power consumption which can be defined as follows:

$$Q \approx V_FID \tag{6}$$

[0066] wherein V_F is the light-emitting element forward voltage, I is the drive current, and D is the PWM duty factor. The difference $\Delta T_{s\text{-}j}$ between the temperature of the light-emitting element package slug and the temperature of the light-emitting element junction can be defined as follows:

$$\Delta T_{s\text{-}j}=QR\Theta_{s\text{-}j} \tag{7}$$

wherein $R\Theta_{s\text{-}j}$ is the thermal resistance of the light-emitting element for a specific packaging and mounting configuration. The light-emitting element junction temperature T_j can be defined as follows:

$$T_j=T_s+\Delta T_{s\text{-}j} \tag{8}$$

wherein T_s is the measured reference temperature, for example a light-emitting element slug temperature.

[0067] In one embodiment of the present invention, the values of the thermal resistances which are required to adequately model the characteristics of a light-emitting element can be determined in a calibration process. For example an embodiment of the present invention can comprise N PWM driven LEDs and a temperature sensor which are all in thermal contact with a printed circuit board (PCB). The PCB temperature T_b as provided by the temperature sensor and the temperature T_{sn} of LED slug n can be defined as follows:

$$T_{sn} = T_b + \Delta T_{bn} D_n \left(1 - \frac{k_n}{3}\left(\sum_{j=1}^{N} D_j - D_n\right)\right) \tag{9}$$

wherein ΔT_{bn} is the temperature difference between the PCB board and the nth LED slug, D_n is the duty factor of the nth LED PWM drive signal, and k_n is the load ratio for the nth LED. For illustrative purposes, example values of ΔT_{bn} and k_n, which were obtained through curve-fitting of experimental data obtained in relation to a specific embodiment of the present invention, are provided in Table 2.

TABLE 2

System thermal model coefficients

Parameter	Red	Amber	Green	Blue
ΔT_{bn} [° C.]	6.60	9.80	11.20	13.30
k_n	0.45	0.35	0.35	0.35

[0068] In one embodiment of the present invention, for some PWM driven light-emitting elements, the intensity of the emitted light can linearly depend on the PWM duty factor. This relation may be used in conjunction with the spectral radiant intensity, the junction temperature and, if desired, one or more desired tristimulus coordinate transformations, to enable the control system to determine the duty factors necessary for driving the light-emitting elements.

[0069] In another embodiment, for some light-emitting elements, the duty factor and the intensity of the emitted light can correlate in a nonlinear fashion. Nonlinearities may be due to various reasons which may include one or more of, for example, transient intensity variations or varying heat load within a duty cycle and exponential cooling and heating of a light-emitting element's junction during transients between ON and OFF portions of a PWM duty cycle. Nonlinearities may be less pronounced in some types of light-emitting elements for high duty factor conditions and may be more pronounced during low duty factor conditions. In one embodiment of the present invention, nonlinearities can be modelled using a second order equation for the intensity-duty factor relationship which can be defined as follows:

$$I = \alpha D^2 + \beta D \tag{10}$$

wherein I is the intensity and D is the PWM drive duty factor. Example values for the constants α and β for a specific embodiment are provided in arbitrary units in Table 3.

TABLE 3

LED intensity PWM duty factor constants

Parameter	Red	Amber	Green	Blue
α	−0.04	−0.13	−0.01	0.02
β	1.04	1.13	1.01	0.98

[0070] In one embodiment of the present invention, the above defined temperature-modified spectral radiant intensity for each colour of light-emitting element can be implemented in firmware as a component of a light-emitting element control system which can utilize temperature feedback to determine control parameters such as duty factors in a feed-forward manner without requiring optical feedback. The control system can be configured to maintain a desired chromaticity within a desired range and accuracy over a range of desired operating temperatures and during dimming, without the need for monitoring emitted light or acquiring optical sensor data and optical feedback or determination or measurement of tristimulus data.

[0071] It is understood that the foregoing models describe parametric relations between spectral radiant intensity, junction temperature and duty factor in conjunction with tristimulus or other suitable colour and intensity coordinates and can be used in any embodiment of a control system which can be configured to solve the set of equations which results from these models to determine the duty factors for each of one or more LEEs or groups of LEEs as a function the desired intensity and chromaticity coordinates, for example, while only requiring feedback information of the operating conditions of the LEEs.

[0072] In one embodiment of the present invention, the desired colour of light can be represented by a coordinate in the CIE 1931 x,y Chromaticity Diagram as illustrated in FIG. **5**. FIG. **5** further illustrates the colour gamut **200** for three coloured light-emitting elements as it would be represented by the CIE 1931 x,y Chromaticity Diagram.

[0073] Based on the particular temperature-modified spectral radiant intensity for each colour of light-emitting element and the desired colour of light, the controller can determine the desired luminous flux output for each colour of light-emitting element in order to obtain the desired colour of light. Based on this evaluated luminous flux output for each colour of light-emitting element, an appropriate control signal can be determined and transmitted to the appropriate light-emitting element(s) for controlling the luminous flux output thereof. Upon the blending of the colours of light created by the light-emitting elements, the desired colour of light can be generated.

[0074] It would be readily understood that different formats of light-emitting elements, for example based on different material compositions, which may produce a similar colour of light, can have different temperature dependencies and would therefore require temperature compensation.

[0075] In one embodiment, a controller can be associated with only a particular set of light-emitting elements. In this manner, the parameters evaluated for modeling the temperature-modified spectral radiant intensity for each of the light-emitting elements of the set, can be integrated into the controller, for example in firmware.

[0076] In another embodiment an alternate means for modeling the temperature sensitivity of the spectral radiant intensity of various colours of light-emitting elements can be integrated into the present invention. For example, a model using a combination of linear and exponential functions to generate a temperature-modified spectral radiant intensity representation for each type of light-emitting element may provide a means for reducing computational time of the control system for determination of control signals for transmission to each of the one or more light-emitting elements of the light source.

[0077] In another embodiment of the present invention, the above defined approximation and associated temperature dependencies of a set of light-emitting elements are used to synthesize training data sets for a neural network-based light-emitting element controller implemented with low-cost microcontrollers for LED intensity and chromaticity control as disclosed in U.S. Pat. No. 7,140,752 and I. Ashdown, Proceedings of Solid State Lighting III, SPIE Vol. 5187, pp. 215-226, 2003), herein incorporated by reference.

[0078] In one embodiment of the present invention the one or more current drivers can use control signals based on a pulse width modulation (PWM) technique for controlling the luminous flux outputs of the light-emitting elements. Since the average output current to the light-emitting elements is proportional to the duty factor of the PWM control signal, it is possible to dim the output light generated by the light-emitting elements by adjusting the duty factors for one or more arrays of light-emitting elements. The frequency of the PWM control signal for the light-emitting elements can be chosen such that the human eye perceives the light output as being constant rather than a series of light pulses, for example a frequency greater than about 60 Hz for example. In another embodiment, the current drivers can use control signals based on pulse code modulation (PCM), or any other digital format as known in the art.

[0079] The functionality of the invention will now be described with reference to specific testing examples. It will be understood that the following testing examples are intended to describe embodiments of the invention and are not intended to limit the invention in any way.

EXAMPLES

[0080] A light source configured according to an embodiment of the present invention, was tested in order to evaluate the functionality of the light source. This embodiment of the light source comprised a defined LED cluster, a sensing device and a control system including a temperature-modified spectral radiant intensity model for each colour of LED. This light source was allowed to thermally stabilize at its respective full intensity and the CCT of the emitted light was set at 3000 Kelvin by adjusting the LED drive currents. Subsequently the LED cluster was de-energized and placed in an environmental chamber for cooling the PCB and attached heat sink to −10° C. The LED cluster was then energized and chromaticity measurements were performed as the temperature of the heat sink stabilized. The respective CCTs and CCT deviations at each temperature are shown in Table 4. In this table, the "CCT Δuv" values represent the deviation from 3000 K along the blackbody locus (corresponding to the measured CCT), while the "3000 K Δuv" values represent the deviation both along and off the blackbody locus.

TABLE 4

Chromaticity fluctuations of example LED cluster set at nominal 3000 K

PCB Temperature (° C.)	CCT (K)	CCT Δuv	3000 K Δuv
15	3060	0.0010	0.0025
17.5	3060	0.0005	0.0023
20	3050	0.0005	0.0020
22.5	3045	0.0004	0.0018
25	3037	0.0002	0.0014
27.5	3033	0.0001	0.0012
30	3030	0.0001	0.0011
32.5	3025	0.0000	0.0009
35	3023	−0.0001	0.0009
37.5	3057	0.0002	0.0022
40	3011	−0.0001	0.0005
42.5	3016	−0.0002	0.0006
45	3011	−0.0002	0.0005
47.5	3046	0.0002	0.0017
50	3010	−0.0002	0.0005
52.5	3015	−0.0001	0.0006
55	3016	−0.0001	0.0007
57.5	3021	−0.0002	0.0008
60	3023	0.0000	0.0008

[0081] In another test, the same light source was set at full intensity and 6500 Kelvin CCT, allowed to thermally stabilize and subsequently de-energized and cooled to −10° C. Again the LED cluster was energized and chromaticity measurements were performed as the temperature of the heat sink stabilized. The respective CCTs and CCT deviations at each temperature are shown in Table 5.

TABLE 5

Chromaticity fluctuations of example LED cluster set at nominal 6500 K

PCB Temperature (° C.)	CCT (K)	CCT Δuv	6500 K Δuv
15	6762	0.0025	0.0034
17.5	6693	0.0017	0.0024
20	6657	0.0014	0.0020
22.5	6641	0.0012	0.0018
25	6612	0.001	0.0014
27.5	6584	0.0007	0.0010
30	6567	0.0005	0.0008
32.5	6547	0.0003	0.0005
35	6557	0.0003	0.0006
37.5	6542	0.0000	0.0005
40	6529	−0.0001	0.0003
42.5	6526	−0.0002	0.0004
45	6512	−0.0003	0.0005
47.5	6496	−0.0005	0.0005
50	6498	−0.0006	0.0006
52.5	6488	−0.0006	0.0007
55	6484	−0.0006	0.0006
57.5	6493	−0.0006	0.0006
60	6491	−0.0005	0.0005

[0082] As illustrated in Tables 4 and 5, the tested embodiment of the light source according to the present invention maintained the LED cluster white light chromaticity to within about $\Delta uv \approx 0.003$ over a range of about 15° C. to 60° C. operating temperature. This is well within the ANSI and IEC chromaticity limits for white light lamps of $\Delta uv = \pm 0.003$ (ANSLG, ANSI C78.376-2001, American National Standards Lighting Group, National Electrical Manufacturers Association, Rosslyn, Va., 2001).

[0083] In another of the performance of the light source configured as defined above, luminous flux output of the LED cluster was dimmed down to 10 percent intensity after thermal stabilization at full intensity with the CCT set to 3000 Kelvin. The results of this test are shown in Table 6.

TABLE 6

Chromaticity of LED cluster over dimming at 3000 K using thermal feedback

Intensity	PCB Temperature (° C.)	CCT (K)	Δuv	Deviation from Target (Δuv)
100%	31.9	3035	0.0001	0.0013
90%	31.2	3045	0.0005	0.0018
80%	30.3	3056	0.0009	0.0023
70%	29.3	3072	0.0011	0.0029
60%	28.2	3086	0.0015	0.0035
50%	27.2	3104	0.0019	0.0043
40%	26.2	3125	0.0025	0.0052
30%	25.2	3155	0.0032	0.0065
20%	24.2	3192	0.0042	0.0082
10%	23.2	3265	0.0063	0.0114

[0084] As shown in Table 6, the controller maintained the LED cluster white light chromaticity to within about $\Delta uv \approx 0.01$ over a dimming range of about 10:1. While this may exceed the ANSI and IEC chromaticity limits for white light lamps, it is noted that these limits apply to lamps operated at full power and 25° Celsius ambient temperature. As would be known to a worker skilled in the art, over their range of operating temperatures and during dimming fluorescent lamp chromaticities vary greater than that identified by the above test of a light source according to an embodiment of the present invention. The known variations of the operational characteristics of fluorescent lamps can be found for example in IESNA, *The IESNA Lighting Handbook: Reference & Application*, Ninth Edition, Illuminating Engineering Society of North America, New York, YK, 2000, for example FIG. 6-45.

[0085] The disclosure of all patents, publications, including published patent applications, and database entries referenced in this specification are specifically incorporated by reference in their entirety to the same extent as if each such individual patent, publication, and database entry were specifically and individually indicated to be incorporated by reference.

[0086] It is obvious that the foregoing embodiments of the invention are exemplary and can be varied in many ways. Such present or future variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

We claim:

1. A light source for generating a desired colour of light, said light source comprising:

a) one or more first light-emitting elements for generating first light having a first wavelength range, the one or more first light-emitting elements responsive to a first control signal;

b) one or more second light-emitting elements for generating second light having a second wavelength range, the one or more second light-emitting elements responsive to a second control signal;

c) one or more sensing devices for generating one or more signals representative of operating temperatures of the one or more first light-emitting elements and the one or more second light-emitting elements; and

d) a control system operatively coupled to the one or more first light-emitting elements, the one or more second light-emitting elements and the one or more sensing devices, the control system configured to receive the one or more signals and configured to determine the first control signal and the second control signal based upon the operating temperatures and the desired colour of light;

wherein the first light and the second light are blended to create the desired colour of light.

2. The light source according to claim **1**, wherein the control system is preconfigured with one or more spectral radiant intensity models for predicting light colour based on operating temperature.

3. The light source according to claim **2**, wherein at least one of the one or more spectral radiant intensity models includes one or more temperature dependent parameters.

4. The light source according to claim **2**, wherein at least one of the one or more spectral radiant intensity models includes one or more Gaussian approximations.

5. The light source according to claim **3**, wherein at least one of the temperature dependent parameters depends linearly on temperature.

6. The light source according to claim **3**, wherein at least one of the temperature dependent parameters depends exponentially on temperature.

7. The light source according to claim **3**, wherein the one or more temperature dependent parameters can be determined in a calibration procedure.

8. The light source according to claim **1**, wherein the control system is preconfigured with a thermal model for predicting operating temperatures of one or more of the first light-emitting elements, or one or more of the second light-emitting elements or both.

9. The light source according to claim **8**, wherein the thermal model depends at least on the first control signal.

10. The light source according to claim **8**, wherein the thermal model depends at least on the second control signal.

11. The light source according to claim **8**, wherein the control system is preconfigured with a thermal model for predicting slug temperatures of the first light-emitting elements or the second light-emitting elements or both.

12. The light source according to claim **8**, wherein the control system is preconfigured with a thermal model for predicting junction temperatures of the one or more first light-emitting elements or the one or more second light-emitting elements or both.

13. The light source according to claim **1**, wherein the first control signal is a pulse width modulated signal having a controllable first duty factor.

14. The light source according to claim **1**, wherein the first control signal is a pulse code modulated signal having a controllable first duty factor.

15. The light source according to claim **1**, wherein the second control signal is a pulse width modulated signal having a controllable second duty factor.

16. The light source according to claim **1**, wherein the second control signal is a pulse code modulated signal having a controllable second duty factor.

17. The light source according to claim **1**, wherein the control system is preconfigured to compensate for non-linear dependencies between the first duty factor and intensity of the first light.

18. The light source according to claim **1**, wherein the control system is preconfigured to compensate for non-linear dependencies between the second duty factor and the intensity of the second light.

19. The light source according to claim **1**, wherein the one or more sensing devices includes one or more temperature sensors.

20. The light source according to claim **1**, wherein the one or more sensing devices includes one or more forward voltage sensors for sensing forward voltage of one or more of the first light-emitting elements.

21. The light source according to claim **1**, wherein the one or more sensing devices includes one or more forward voltage sensors for sensing forward voltage of one or more of the second light-emitting elements.

22. A method for generating a desired colour of light, the method comprising the steps of:

a) determining a first operating temperature of one or more first light-emitting elements which provide first light having a first spectrum;

b) determining a second operating temperature of one or more second light-emitting elements which provide second light having a second spectrum;

c) providing a first spectral radiant intensity model indicative of effects of the first operating temperature on the first spectrum;

d) providing a second spectral radiant intensity model indicative of effects of the second operating temperature on the second spectrum;

e) determining a first control signal and a second control signal based upon the first spectral radiant intensity model, the second spectral radiant intensity model, the desired colour of light and the first operating temperature and second operating temperature;

f) providing the first control signal to the one or more first light-emitting elements;

g) providing the second control signal to the one or more second light-emitting elements; and

h) blending the first light and the second light into mixed light having the desired colour of light.

23. The method according to claim **22**, wherein at least one of the first spectral radiant intensity model and the second spectral radiant intensity model include one or more Gaussian approximations.

24. The method according to claim **22**, wherein the first operating temperature and the second operating temperature are slug temperatures.

25. The method according to claim **22**, wherein the first operating temperature and the second operating temperature are junction temperatures.

26. The method according to claim **22**, wherein the first control signal is a pulse-width modulated signal having a controllable first duty factor.

27. The method according to claim **22**, wherein the first control signal is a pulse-code modulated signal having a controllable first duty factor.

28. The method according to claim **22**, wherein the second control signal is a pulse-width modulated signal having a controllable second duty factor.

29. The method according to claim **22**, wherein the second control signal is a pulse-code modulated signal having a controllable second duty factor.

30. The method according to claim **22**, further comprising the step of providing a thermal model for predicting the first operating temperature and second operating temperature based on the first control signal and second control signal.

31. The method according to claim **30**, wherein the thermal model includes non-linear dependencies between the first operating temperature and second operating temperature and the first control signal and the second control signal.

* * * * *

US007055986B2

(12) **United States Patent**
Littleton

(10) **Patent No.: US 7,055,986 B2**
(45) **Date of Patent: Jun. 6, 2006**

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(54) **PROGRAMMABLE LED SPECTRAL LIGHT SOURCE**

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(73) Assignee: **The United States of America as represented by the Secretary of the Army**, Washington, DC (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 216 days.

(21) Appl. No.: **10/792,850**

(22) Filed: **Mar. 5, 2004**

(65) **Prior Publication Data**

US 2005/0194516 A1 Sep. 8, 2005

(51) **Int. Cl.**
F21V 9/16 (2006.01)
F21V 29/00 (2006.01)

(52) **U.S. Cl.** **362/231**; 362/235; 362/251; 362/276; 362/294; 362/373

(58) **Field of Classification Search** 362/230–231, 362/235–236, 276, 373, 800, 802, 249, 251, 362/294
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,608,213 A *	3/1997	Pinkus et al.	....	250/252.1
5,679,949 A *	10/1997	Task et al.	....	250/252.1
5,686,210 A *	11/1997	Sharman	....	430/30
5,783,909 A *	7/1998	Hochstein	....	315/159
5,982,957 A *	11/1999	DeCaro et al.	....	382/312
6,127,783 A *	10/2000	Pashley et al.	....	315/149
6,441,558 B1 *	8/2002	Muthu et al.	....	315/149
6,759,814 B1 *	7/2004	Vogel et al.	....	315/312
2003/0233138 A1 *	12/2003	Spooner	....	607/93

OTHER PUBLICATIONS

J. Res. Natl. Inst. Stand. Technol. 107, 363-371 Jul. 2002, Development of a Tunable LED-Based Colorimetric Source, Steven W. Brown, et. al.

Nist Tech Beat Apr. 23, 2004, http://www.nist.gov/public_affairs/techbeat/tb2004_0423.htm Portable 'Rainbow' Source Improves Color Calibrations, Laura Ost.

* cited by examiner

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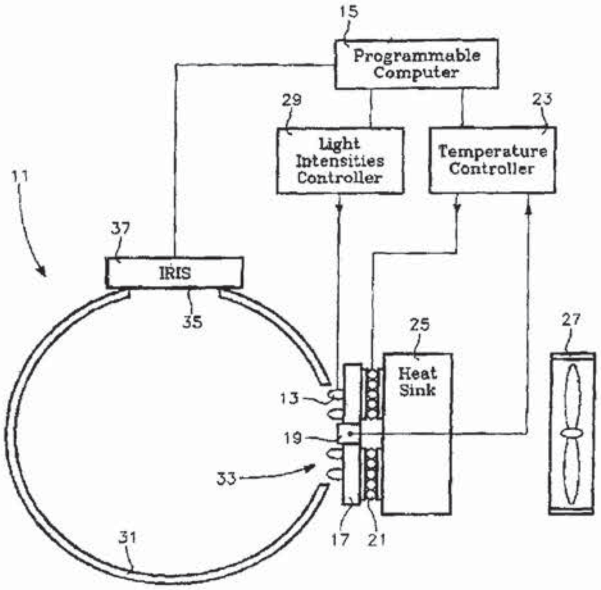
(57) **ABSTRACT**

An apparatus for emulating various known night sky illumination conditions. The apparatus comprises a plurality of electrically-powerable LEDs which are disposed in an array and have respective spectral curves centered at different wavelengths in the visible to the short wave infrared wavebands, and means for fixing the temperatures of the LEDs to avoid temperature-induced changes in their spectral curves. Additionally, the apparatus includes means for varying the light intensities of the individual LEDs so that the combination of their spectral curves matches the spectrum of the known night sky illumination condition to be emulated, and means for regulating the total amount of light collected from the array so that the cumulative spectrum has the same intensity as the known night sky illumination condition to be emulated.

18 Claims, 1 Drawing Sheet



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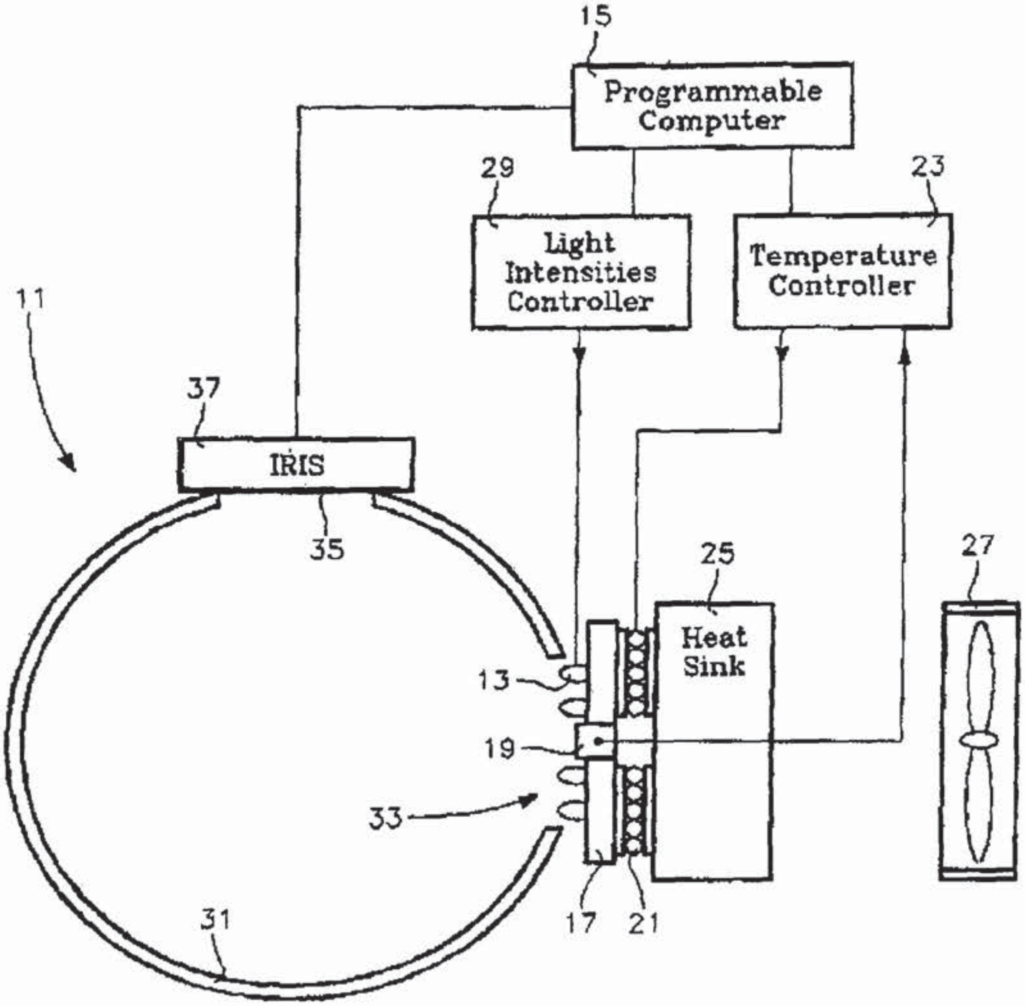
15
Programmable Computer
29
Light Intensities Controller
23
Temperature Controller
11
37
IRIS
35
25
Heat Sink
27
13
19
33
31
17
21

FIG. 1

PROGRAMMABLE LED SPECTRAL LIGHT SOURCE

GOVERNMENT INTEREST

The invention described herein may be manufactured, used, sold, imported, and/or licensed by or for the Government of the United States of America.

BACKGROUND OF THE INVENTION

This invention relates in general to light sources, and more particularly, to programmable light sources.

The performance of passive low-light-level imaging systems that operate in the visible, near infrared, and short wavelength infrared spectral bands has been investigated for the past several years. Although such devices operate under low power, exhibit low dark current, and retain high system resolution under moonlight conditions, they are limited under low light level conditions.

Typically, their performance is evaluated in a laboratory setting using a 2856° K blackbody—a tungsten filament—as the radiation source, which can correlate reasonably well with night sky measurements below 1 micron. However, it does not correlate reasonably well with night sky measurements above 1 micron. Night sky spectral irradiance data indicate that a moonless sky produces over an order of magnitude more photons in the short-wave infrared (1 to 2 micron) waveband than in the visible and near infrared (0.4 to 1.0 micron) waveband. Therefore, the use of a single broadband 2856° K source in a laboratory to evaluate imaging systems that operate beyond 1 micron is insufficient.

SUMMARY OF THE INVENTION

It is therefore an object of this invention to accurately evaluate in a laboratory setting passive low-light-level imaging systems that operate in the visible, near infrared, and short wavelength infrared spectral bands.

This and other objects of the invention are achieved in one aspect by an apparatus for emulating various known spectral signatures, particularly night sky illumination conditions. The apparatus comprises a plurality of electrically-powerable LEDs which are disposed in an array and have respective spectral curves centered at different wavelengths in the visible to the short wave infrared wavebands, and means for fixing the temperatures of the LEDs to avoid temperature-induced changes in their spectral curves. Additionally, the apparatus includes means for varying the light intensities of the individual LEDs so that the combination of their spectral curves matches the spectrum of the known night sky illumination condition to be emulated, and means for regulating the total amount of light collected from the array so that the cumulative spectrum has the same intensity as the known night sky illumination condition to be emulated.

Another aspect of the invention involves a method of emulating various spectral signatures comprising the steps of: (a) electrically-powering a plurality of electrically-powered LEDs in an array, the LEDs having respective spectral curves centered at different wavelengths in the visible to the short wave infrared wavebands; (b) fixing the temperatures of the LEDs to avoid temperature-induced changes in their spectral curves; (c) varying the light intensities of the individual LEDs so that the combination of their spectral curves matches the spectrum of the known night sky illumination condition to be emulated; and (d) regulating the total amount of light collected from the array so that the cumulative spectrum has the same intensity as the known night sky illumination condition to be emulated.

The invention can accurately emulate various night sky illumination conditions by emitting spectra in a laboratory setting to match that of full moon, partial moon, starlight and overcast starlight conditions.

Additional advantages and features will become apparent as the subject invention becomes better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings wherein:

BRIEF DESCRIPTION OF THE DRAWINGS

The sole FIGURE is a schematic illustration of an illumination conditions-emulating apparatus embodying the invention.

WRITTEN DESCRIPTION OF THE PREFERRED EMBODIMENT

The FIGURE shows the apparatus **11** for emulating various known spectral signatures such as night sky illumination conditions. The apparatus **11** comprises an electrically-powered array **13** of LEDs which have respective spectral curves centered at different wavelengths in the visible to the short wavelength infrared wavebands, specifically in the 0.4 to 2.5 micron range, and means for fixing the temperatures of the LEDs to avoid temperature-induced changes in their spectral curves. Additionally, the apparatus **11** includes means for varying the light intensities of the individual LEDs so that the combination of their spectral curves matches the spectrum of the known night sky illumination condition to be emulated, and means for regulating the total amount of light collected from the array so that the cumulative spectrum has the same intensity as the known night sky illumination condition to be emulated.

While the temperature-fixing means may take a variety of forms, conveniently it may take the form shown of a programmable computer **15**, a copper plate **17** thermally connected to the LED array **13**, a temperature sensor **19** that is in thermal communication with copper plate **17** and electrically connected to temperature controller **23**. A plurality of thermo-electric coolers **21** connected to the copper plate for providing an input to the programmable computer, a temperature controller **23** connected to the computer, to the temperature sensor **19** and to the coolers, a heat sink **25** connected to the coolers, and a cooling fan **27** disposed next to the coolers.

While the light-intensities-varying means may take a variety of means, conveniently it may take the form shown of the programmable computer **15**, and a light-intensities controller **29** connected between the LED array **13** and the computer.

While the light-regulating means may take a variety of forms, conveniently it may take the form shown of the programmable computer **15**, an integrating sphere **31** attached to the LED array **13**, the sphere having an input opening **33** and an output opening **35**, and an iris **37** mounted on the output opening of the sphere and connected to the programmable computer.

For the materials of the present invention, the preferred temperature sensor is a Model W2142 platinum resistance thermometer device manufactured by Omega. The preferred thermo-electric coolers are model CP1.0-71-05L-1 coolers made by Melcor, while LEDs manufactured by Roithner

LasertechniK, of Vienna can be used. The preferred integrating sphere is a custom six-inch sphere mad by Spectra-Physics. The light intensity controller and temperature controller can be manufactured using readily available commercial electronic components in a manner known by the skilled artisan.

In operation, the array **13** of LEDs is electrically-powered and the temperatures of the LEDS are fixed to avoid temperature-induced changes in their spectral curves. This is done by monitoring heat-generated temperature changes in the temperature of the copper plate **17** and thus in the temperature of the LED array **13** with the temperature sensor **19**. Temperature sensor **19** provides an input to the temperature controller according to the temperature of the copper plate. The temperature sensor, in response to a command from programmable computer **15** to maintain a predetermined temperature, uses the temperature sensor input to drive the thermo-electric coolers **21** and cool the LED array, by removing heat generated by the thermo-electric coolers with the heat sink **25** and the cooling fan **27**. With this configuration, the LED array temperature is continuously driven to be equal to a fixed predetermined temperature.

Next, the integrating sphere **31** collects at its input opening **33** light from the LED array **13** and outputs at its output opening **35** a uniform distribution of the light collected from the array. The light intensities controller **29** controls the electric power provided to the individual LEDs from their power supply (not shown), and thus their light intensities, in response to commands from the programmable computer **15** so that the combination of their spectral curves matches the known night sky illumination condition to be emulated, and the iris **37** adjusts the size of the output opening **35** of the integrating sphere **31** in response to commands from the programmable computer **15** so that the cumulative spectrum has the same intensity as the known night sky illumination condition to be emulated.

It is obvious that many modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as described.

What is claimed as new and desired to be secured by Letters Patent of the united states is:

1. An apparatus for emulating spectral signatures comprising:

a plurality of electrically-powerable LEDs disposed in an array, the LEDs having respective spectral curves centered at different wavelengths in the visible to the short wave infrared wavebands;

means for fixing the temperatures of the LEDs to avoid temperature-induced changes in their spectral curves;

means for varying the light intensities of the individual LEDs so that the combination of their spectral curves matches the spectrum of an illumination condition to be emulated; and

means for regulating the total amount of light collected from the array so that the cumulative spectrum has the same intensity as the illumination condition to be emulated,

wherein the light-regulating means includes an integrating sphere attached to the LED array, the integrating sphere having an input opening for collecting light from the array and an output opening for outputting a uniform distribution of the collected light, and

an iris mounted on the output opening of the integrating sphere for adjusting the size of the output opening.

2. The apparatus recited in claim **1** where the temperature-fixing means includes a programmable computer.

3. The apparatus recited in claim **2** wherein the temperature-fixing means includes a copper plate thermally connected to the LED array.

4. The apparatus recited in claim **3** wherein the temperature-fixing means includes a temperature sensor connected to the copper plate and to the computer for monitoring heat-generated changes in the temperature of the LED array and feeding the information to the computer.

5. The apparatus recited in claim **1** wherein the light-intensities-varying means includes a programmable computer.

6. The apparatus recited in claim **5** wherein the light-intensities-varying means includes a light intensity controller connected to the LED array and to the programmable computer for varying the light intensities of the individual LEDs in response to commands from the computer.

7. The apparatus recited in claim **1** wherein the light-regulating means includes a programmable computer.

8. An apparatus for emulating various known spectral signatures comprising:

a plurality of electrically-powerable LEDs disposed in an array, the LEDs having respective spectral curves centered at different wavelengths in the visible to the short wave infrared wavebands;

means for fixing the temperatures of the LEDs to avoid temperature-induced changes in their spectral curves;

means for varying the light intensities of the individual LEDs so that the combination of their spectral curves matches the spectrum of a known night sky illumination condition to be emulated; and

means for regulating the total amount of light collected from the array so that the cumulative spectrum has the same intensity as the known night sky illumination condition to be emulated,

wherein the temperature-fixing means includes;

a programmable computer,

a copper plate thermally connected to the LED array,

a temperature sensor connected to the copper plate and to the computer for monitoring heat-generated changes in the temperature of the LED array and feeding the information to the computer, and

a plurality of thermo-electric coolers connected to the copper plate for cooling the LED array.

9. The apparatus recited in claim **8** wherein the temperature-fixing means includes a temperature controller connected to the computer and to the thermo-electric coolers for driving the coolers in response to commands from the computer to cool the LED array.

10. The apparatus recited in claim **9** wherein the temperature-fixing means includes a heat sink connected to the thermo-electric coolers for removing heat generated by the coolers.

11. The apparatus recited in claim **10** wherein the temperature-fixing means includes a cooling fan disposed next to the thermo-electric coolers for removing heat generated by the coolers.

12. An apparatus for emulating various known spectral signatures comprising:

a plurality of electrically-powerable LEDs disposed in an array, the LEDs having respective spectral curves centered at different wavelengths in the visible to the short wave infrared wavebands;

means for fixing the temperatures of the LEDs to avoid temperature-induced changes in their spectral curves;

means for varying the light intensities of the individual LEDs so that the combination of their spectral curves matches the spectrum of a known night sky illumination condition to be emulated; and

means for regulating the total amount of light collected from the array so that the cumulative spectrum has the same intensity as the known night sky illumination condition to be emulated,

wherein the light-regulating means includes an integrating sphere attached to the LED array, the integrating sphere having an input opening for collecting light from the array and an output opening for outputting a uniform distribution of the collected light,

a programmable computer, and

an iris mounted on the output opening of the integrating sphere and connected to the programmable computer for adjusting the size of the output opening in response to commands from the computer.

13. An apparatus for emulating various night sky illumination conditions comprising:

a plurality of electrically-powerable LEDs disposed in an array, the LEDs having respective spectral curves centered at different wavelengths in the 0.4 to 2.5 micron range;

a programmable computer;

a copper plate thermally connected to the LED array;

a temperature sensor connected to the copper plate and to the computer for monitoring changes in the temperature of the LED array resulting from generation of heat by the LED array and feeding the information to the computer;

a plurality of thermo-electric coolers connected to the copper plate for cooling the LED array;

a temperature controller connected to the computer and to the coolers for driving the coolers in response to commands from the computer to cool the LED array;

a heat sink connected to the coolers for removing heat generated by the coolers;

a cooling fan disposed next to the coolers for removing heat generated by the coolers;

a light intensity controller connected between the LED array and the computer for varying the light intensities of the individual LEDs in response to commands from the computer;

an integrating sphere attached to the LED array, the sphere having an input opening for collecting light from the array and an output opening for outputting a uniform distribution of the light collected front the array; and

an iris mounted on the output opening of the integrating sphere and connected to the computer for adjusting the size of the output opening in response to commands from the computer.

14. A method of emulating spectral signatures comprising the steps of:

(a) electrically powering a plurality of LEDs in an array, the LEDs having respective spectral curves centered at different wavelengths in the visible to the short wave infrared wavebands;

(b) fixing the temperatures of the LEDs to avoid temperature-induced changes in their spectral curves;

(c) varying the light intensities of the individual LEDs so that the combination of their spectral curves matches the spectrum of an illumination condition to be emulated; and

(d) regulating the total amount of light collected from the array so that the cumulative spectrum has the same intensity as the illumination condition to be emulated,

wherein step (d) includes:

collecting light from the array and outputting a uniform distribution of the collected light through an opening, and

adjusting the size of the opening.

15. The method recited in claim **14** wherein step (b) includes:

monitoring heat-generated changes in the temperature of the LED array.

16. The method recited in claim **15** wherein step (b) includes:

feeding the monitored changes to a programmable computer.

17. The method recited in claim **14** wherein step (b) includes:

cooling the LED array.

18. A method of emulating various spectral signatures comprising the steps of:

(a) electrically powering a plurality of LEDs in an array, the LEDs having respective spectral curves centered at different wavelengths in the visible to the short wave infrared wavebands;

(b) fixing the temperatures of the LEDs to avoid temperature-induced changes in their spectral cvrves;

(c) varying the light intensities of the individual LEDs so that the combination of their spectral curves matches the spectrum of a known night sky illumination condition to be emulated; and

(d) regulating the total amount of light collected from the array so that the cumulative spectrum has the same intensity as the known night sky illumination condition to be emulated,

wherein step (d) includes:

collecting light from the array and outputting a uniform distribution of the collected light through an opening,

adjusting the size of the opening in response to commands from a programmable computer.

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